WITAMIR-I Neutronics - Papers Presented in 1980 on Tandem Mirror Reactor Central Cell Neutronics

R.T. Perry and C.W. Maynard

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Papers Presented at: Annual Meeting of The American Nuclear Society, Las Vegas, Nevada, June 1980; and Eleventh Symposium on Fusion Technology, Oxford, England, September 1980.

Preface

This UWFDM contains two papers presented on WITAMIR-I central cell neutronic calculations. WITAMIR-I is a conceptual tandem mirror fusion reactor that was developed in a design study at the University of Wisconsin.

The first paper, found in Part I of this report, was presented at the June 1980 Annual Meeting of the American Nuclear Society. The summary is published in Volume 34 of the Transactions of the ANS. This paper presents the results of parametric neutronic studies made in order to establish a basic blanket design.

The second paper, in Part II of this report, was presented at the Eleventh Symposium on Fusion Technology at Oxford, England in September 1980. The paper, which will be published in the proceedings of this conference, presents the neutronic results for the final blanket design of WITAMIR-I.

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Part I

A Neutronic Study of

a Lithium-Lead Cooled

Tandem Mirror Reactor

Presented at the June

1980 Annual Meeting

of the American Nuclear Society

1. Summary - Published in Volume 34 of the Transactions of the American Nuclear Society, June 1980

5. A Neutronic Study of a Lithium-Lead-Cooled Tandem Mirror Reactor Blanket, *R. T. Perry, C. W. Maynard (Univ of Wis)*

A parametric neutronic study of a fusion reactor blanket shield and magnet which utilizes a eutectic mixture of lithium and lead as the coolant/breeder is discussed. These calculations were made as a part of an ongoing conceptual design study of a tandem mirror reactor[1] at the University of Wisconsin.

The blanket will consist of a series of tube banks made of the ferritic steel, HT-9, running circumferentially around the plasma reaction chamber. A eutectic mixture of $Li_{17}Pb_{83}$ flows through the tubes to provide cooling and tritium production. The tube bank is followed by a reflector/shield. This is then followed by 0.2 m of thermal insulation and the magnets. For the results presented here, the plasma chamber has a first-wall radius of 1.1 m and a length of 92 m.

The neutronic and photonic calculations were made with the one-dimensional code ANISN.[2] A P3-S8 approximation in cylindrical geometry was used in the transport calculation. The transport cross sections were a coupled 25-neutron/21-gamma-group data library created from the RSIC DLC-41B/Vitamin C Data Library.[3] Kerma factors, helium and hydrogen production cross section, and displacement cross sections were created from the DLC-60/MACLIB-IV Data Library.[4] A standard CTR weighing function was used to collapse the DLC-60 and DLC-41B Libraries into the 25-neutron and 21-gamma-energy-group structures.

In the first set of parametric calculations, the volume percent of structural material in the blanket was varied from 0 to 50 vol%. The composition of the structural material was 11 wt% chromium and 89 wt% iron. These calculations were made to determine the effects of the structural material on the tritium breeding ratio so that limits on the blanket thickness could be set. A 1-m-thick blanket was used in these calculations. The reflector and shield were not considered here. For conservative estimates, a vacuum boundary condition was used on the outside of the blanket.

The breeding ratio varied almost linearly as a function of volume percent of structural material in the blanket. At 22% structure, the breeding ratio was 1.0 and increased to a value of 1.4 at 0% structure. Concurrent geometrical calculations noted that 10 vol% structure was a reasonable value. Using this value, these neutronic calculations indicated that a tritium breeding ratio of 1.1, a design goal, could be obtained within a 0.75-m blanket.

Using these numbers as a basis, two basic blanket/shield designs were evaluated. The first design had a breeding blanket of 0.75 m followed by a ferritic steel reflector of 0.25 m, and then a shield of 0.5-m thickness. The breeding blanket was composed of 90% $Li_{17}Pb_{83}$ and 10% ferritic steel structure. The reflector was composed of 95% ferritic steel and 5% water. The shield was 60% ferritic steel, 15% lead, 15% boron carbide, 5% water, and 5% void.

The second blanket/shield design eliminated the reflector, thus extending the breeding blanket to 1-m thickness. This was also followed by a 0.5-m shield. In both cases, the shield was followed by 0.2 m of insulation and then the 0.8-m magnet. For calculational purposes, the magnet consisted of 60% aluminum, 30% copper, and 10% helium.

The first case resulted in the release of 18.9 MeV per 14-MeV neutron, an energy multiplication of 1.34. Sixty percent, or 11.3 MeV of the energy deposited, was due to gamma interactions. Ten percent of the total energy was deposited in the reflector, and it is expected that this energy will be recoverable. Less than 1% of the energy was deposited in the shield. The tritium breeding ratio was 1.10.

In the second case, a total of 18.0 MeV per 14-MeV neutron was deposited in the blanket and shield, an energy multiplication of 1.28. Since the breeding zone increases in thickness, the breeding ratio also increases to 1.18. The energy deposited from the neutron collisions and charged-particle reactions increases from 7.60 MeV in the previous case to 8.23 MeV here, and is primarily related to the increased tritium production. The gamma energy deposited, 9.77 MeV, decreases due to the reduction in capture gammas from lead, iron, and chromium since more neutrons are captured in lithium. This accounts for the reduction in energy multiplication from the previous case since about 7 MeV is released from a capture in lead, iron, or chromium as compared to 4.8 MeV released from a capture in ^6Li.

Thus in a lithium-lead blanket, the energy multiplication is enhanced by low lithium content in the blanket by two means. First, there is a greater probability a high-energy neutron collision will result in an (n,2n) or (n,3n) reaction in lead, and therefore, increased neutron production. Secondly, a neutron capture in the structural material or lead results in a greater energy release than if captured in lithium. To emphasize this point, we enriched the ^6Li in case two to 95%. The breeding ratio increases to 1.64; however, the total energy production drops to 16.4 MeV per 14-MeV neutron.

Currently, because of its high energy multiplication, we chose the blanket/reflector/shield combination in the first case as our base design; although it is subject to change pending economic and further engineering analysis. In addition, we find that the shield adequately protects the magnets. In the magnets, the heat deposited is 8.7×10^{-8} W/cm^3 and a maximum of 6.0×10^{-6} dpa/yr in the copper stabilizer per 1 MW/m^2 first-wall neutron load.

1. B. BADGER et al., "Preliminary Information on the University of Wisconsin Tandem Mirror Reactor Design," UWFDM-325, University of Wisconsin (Nov. 1979).
2. W. W. ENGLE, Jr. "Anisn, A 1-D Discrete Ordinates Transport Code with Anistropic Scattering," ORNL-K-1693 (1973).
3. RSIC Data Library Collection, "Vitamin-C, 171 Neutron, 36 Gamma-Ray Group Cross Section Library in AMPX Interface Format for Fusion Neutronics Studies," DLC-41, ORNL.
4. RSIC Data Library Collection, "MACKLIB-IV, 171 Neutron, 36 Gamma-Ray Group Kerma Factor Library," DLC-60, ORNL.

2. Text of the Paper - Presented at
the June 1980 Annual Meeting
of the American Nuclear Society
Las Vegas, Nevada

A Neutronic Study of a Lithium-Lead Cooled Tandem Mirror Reactor Blanket

R.T. Perry C.W. Maynard
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Abstract

A parametric neutronic study of a fusion reactor blanket, shield, and magnet which utilizes a eutectic mixture of lithium and lead as the coolant/breeder is discussed. These calculations were made as part of an ongoing conceptual design study of a Tandem Mirror Reactor at the University of Wisconsin.

1. Introduction

In this paper we discuss the parametric neutronic study that was made in order to establish the blanket for a conceptual tandem mirror fusion reactor.(1) Since these calculations were a part of an ongoing study, results obtained from a particular parameter study were subject to iteration due to changes in wall loads, plasma radius, and magnet design. These changes, however, usually have only a secondary effect on normalized results. For this reason the results presented in this paper are normalized to a wall load of 1 MW/m^2; however, they may be scaled to any desired value.

Basically, the purpose of the parameter studies was to determine the blanket and shield thickness, determine if a reflector was needed, and determine the percent structural material. These items are subject to certain constraints and requirements such as the necessity to breed tritium, provide adequate protection for the magnets, and to maximize energy production.

It is envisioned that the blanket will consist of a series of tube banks made of the ferritic steel, HT-9, running circumferentially around the plasma reaction chamber. A eutectic mixture of $Li_{17}Pb_{83}$ flows through the tubes to provide cooling and tritium production. The tube bank is followed by a reflector/shield. This is followed by thermal insulation and then the magnets. A cross sectional view of the reactor is shown in Figure 1.

In the following sections we discuss in more detail the methodology used, the calculations made, and the results obtained for this design.

2. Methodology and Data

The neutronic and photonic calculations were made with the one dimensional code ANISN.[2] A P3-S8 approximation in cylindrical geometry was used in the transport calculation. The transport cross sections were a coupled 25 neutron-21 gamma group data library created from the RSIC DLC-41B/Vitamin C Data Library.[3] Kerma factors, helium and hydrogen production cross sections, and displacement cross sections were created from the DLC-60/MACKLIB-IV[4] Data Library. A standard CTR weighting function was used to collapse the DLC-60 and DLC-41B libraries into the 25 neutron and 21 gamma energy group structures.

3. Basic Blanket Design

In the first set of parametric calculations, the volume percent of structural material in the blanket was varied from zero to 90 volume percent. The composition of the structural material was 11 weight percent chromium and 89 weight percent iron. These calculations were made in order to determine the effects of the structural material on the tritium breeding ratio so that limits on the blanket thickness could be set. A one meter thick blanket was used in these calculations. The reflector and shield were not considered

CROSS SECTION OF WITAMIR I CENTRAL CELL

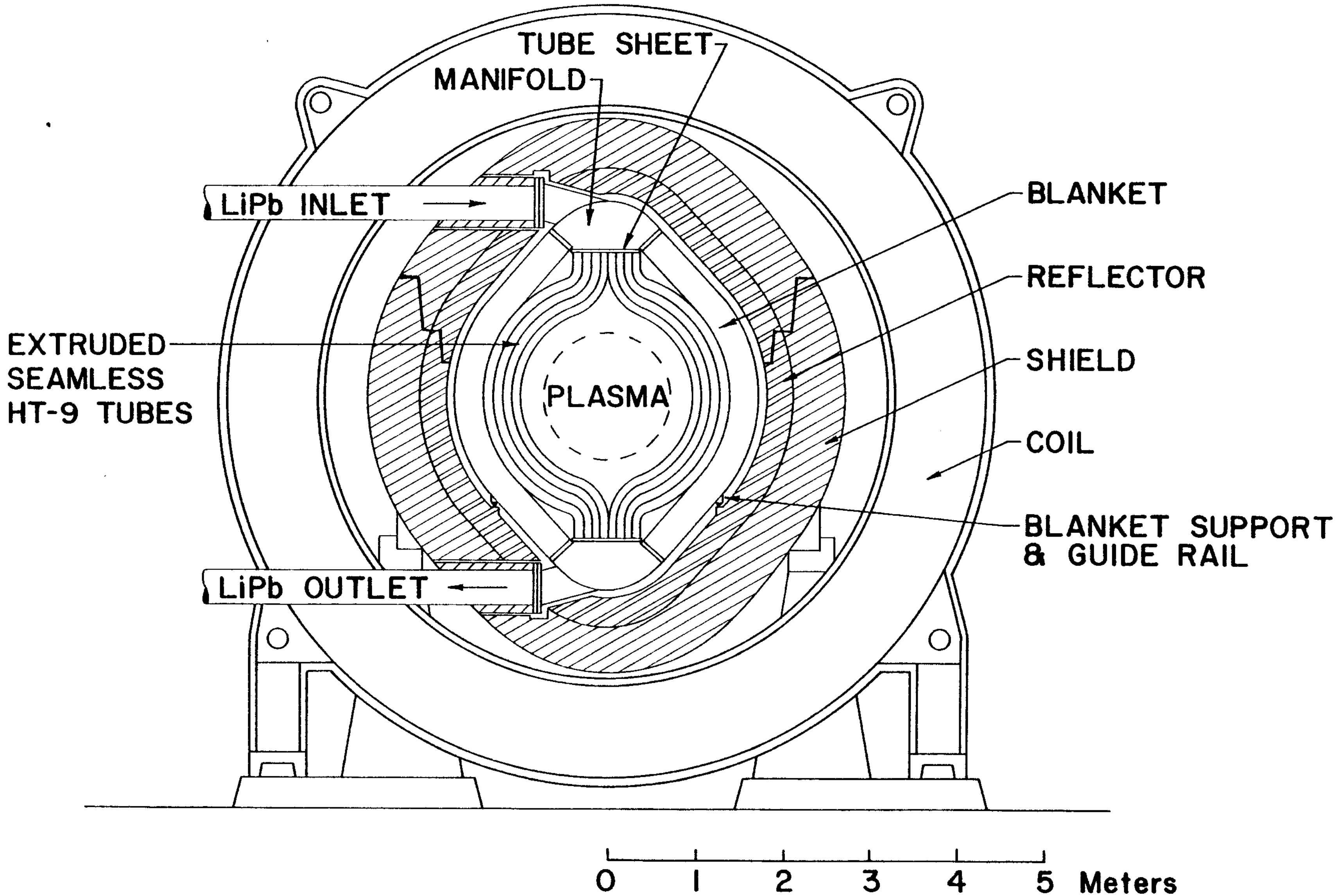


Figure 1

here. For conservative estimates, a vacuum boundary condition was used on the outside of the blanket. The results are plotted in Figure 2.

As may be noted in Figure 2, the breeding ratio varied almost linearly as a function of volume percent of structural material in the blanket. At 22 percent structure, the breeding ratio was 1.0 and increased to a value of 1.4 at zero percent structure. From the standpoint of the tritium breeding requirement, the blanket could contain up to 22% structure. This is a conservative estimate since the blanket could be made much thicker than the one meter with vacuum boundary conditions at which these cases were evaluated.

In order to estimate the effect of radius on the tritium production, two of the above cases containing 5% and 10% structure were considered. The tritium production was integrated from the inner radius to a variable depth giving the cumulative production to that depth. This is shown in Figure 3 and is similar to the breeding ratio of a blanket of that thickness with some reflector.

In concurrent geometrical calculations it was noted that 10 volume percent was a reasonable value. Using this value and the results obtained from Figure 3 indicated that a tritium breeding ratio of ~ 1.1, a design goal, could be obtained within a .75 meter blanket.

Using these results as a basis, two basic blanket/shield designs were evaluated. The first design had a breeding blanket of .75 meters followed by a ferritic steel reflector of .25 meters, and then a shield of .5 meter thickness. The breeding blanket was composed of 90 percent $Li_{17}Pb_{83}$ and 10 percent ferritic steel structure. The reflector was composed of 95 percent ferritic steel and 5 percent water. The shield was 60 percent ferritic steel, 15

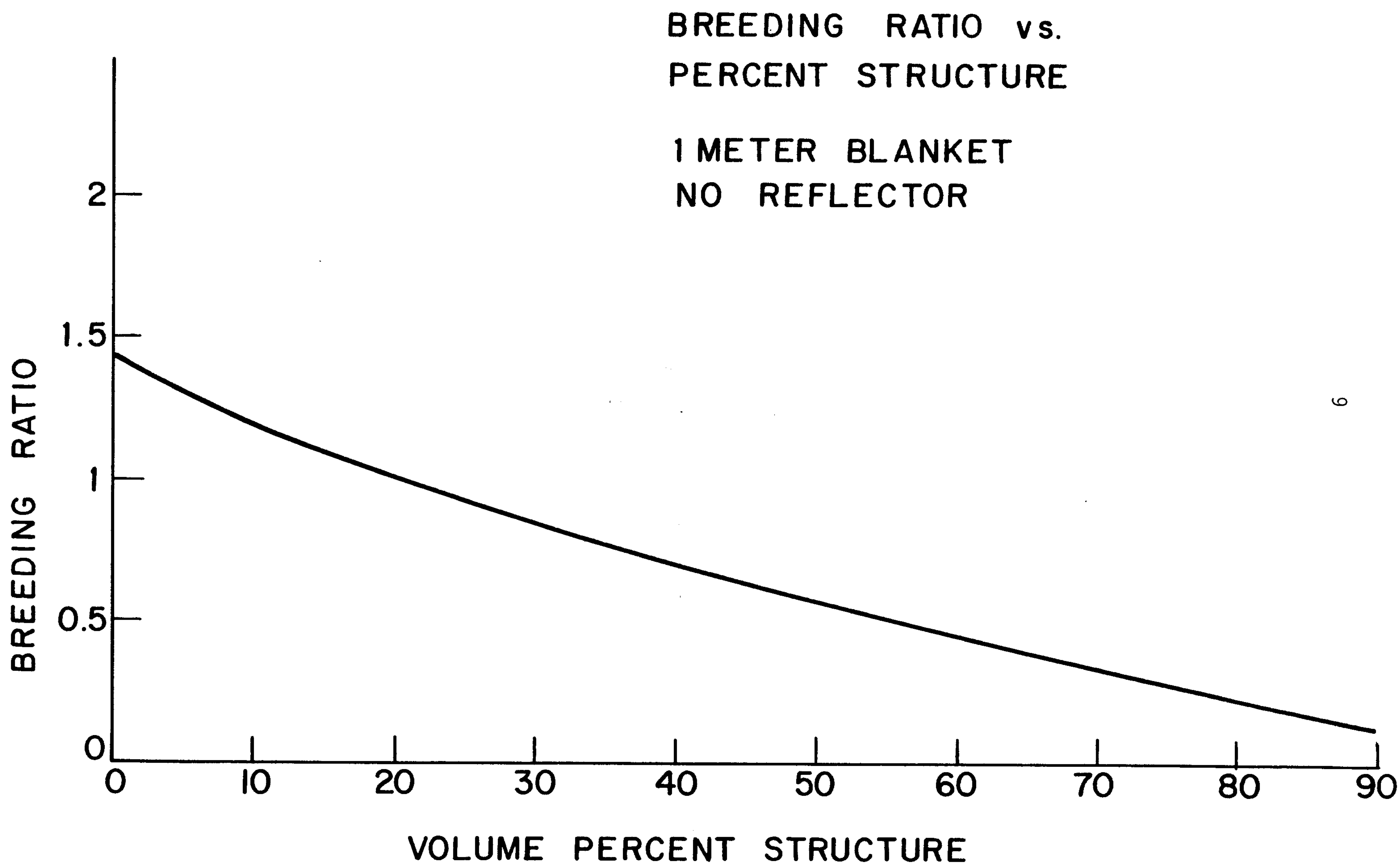

BREEDING RATIO vs.
PERCENT STRUCTURE
1 METER BLANKET
NO REFLECTOR
BREEDING RATIO
0
0.5
1
1.5
2
0
10
20
30
40
50
60
70
80
90
VOLUME PERCENT STRUCTURE

Figure 2

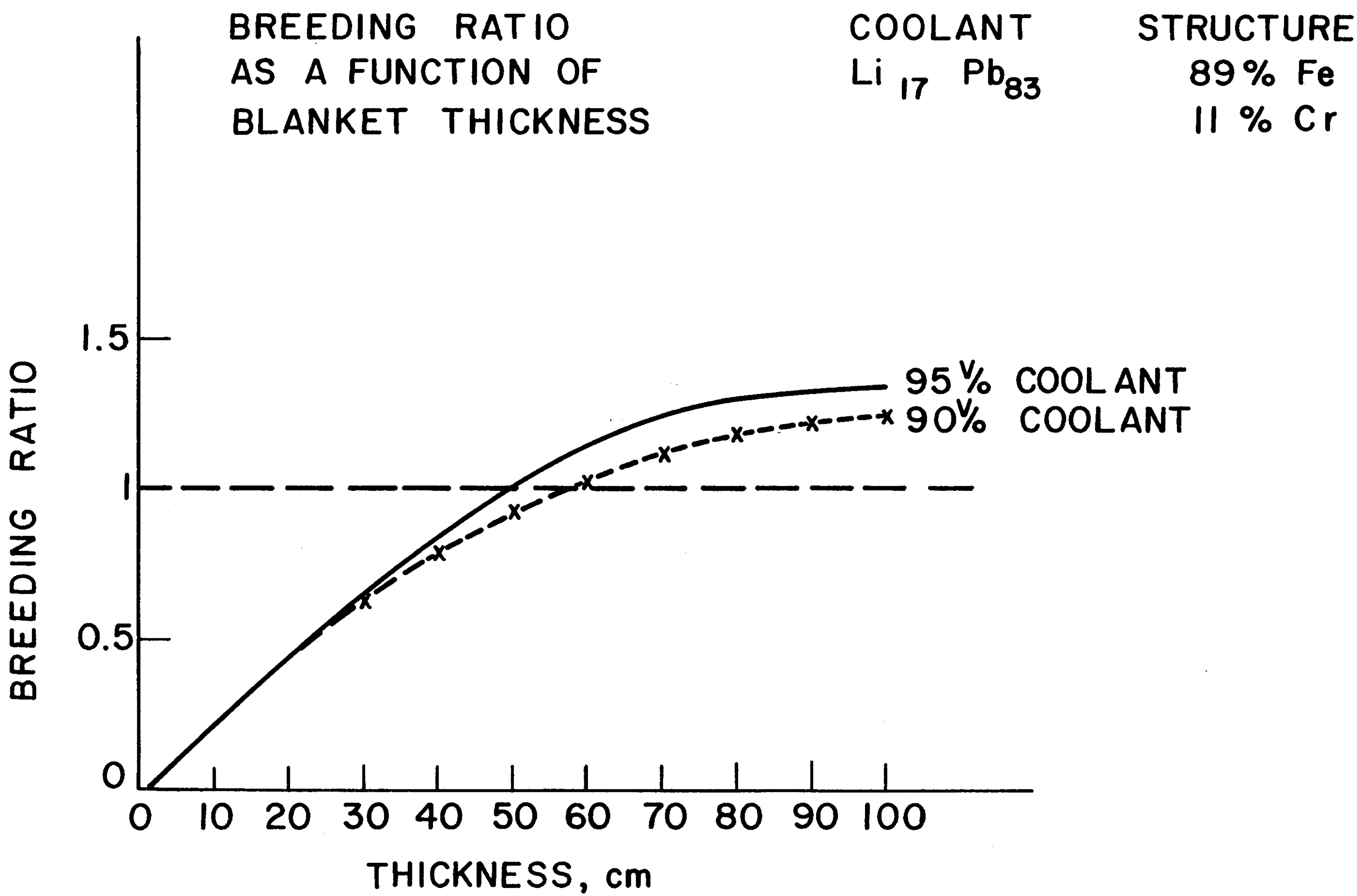

BREEDING RATIO
AS A FUNCTION OF
BLANKET THICKNESS
COOLANT
Li 17 Pb83
STRUCTURE
89% Fe
11 % Cr
95 V/o COOLANT
90 V/o COOLANT
BREEDING RATIO
1.5
1
0.5
0
0 10 20 30 40 50 60 70 80 90 100
THICKNESS, cm

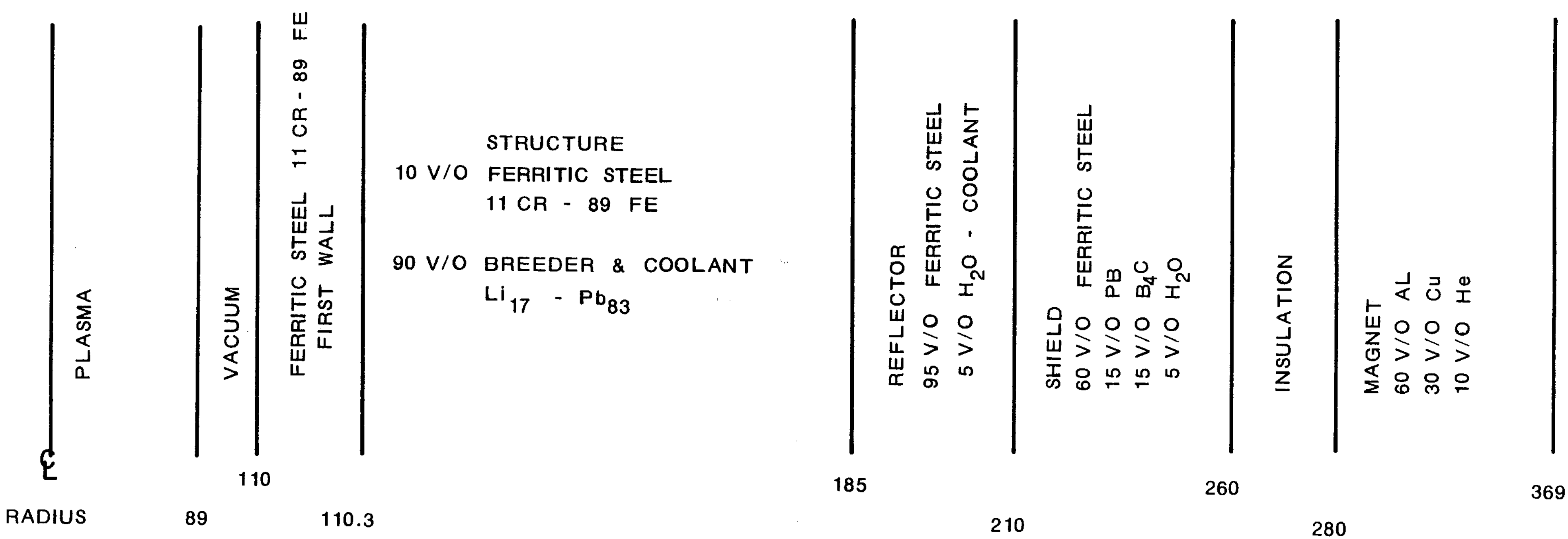
Figure 3

percent lead, 15 percent boron carbide, 5 percent water, and 5 percent void. A schematic of this blanket/shield is shown in Figure 4.

The second blanket/shield design eliminated the reflector, thus extending the breeding blanket to one meter thickness. This was also followed by a .5 meter shield. In both cases, the shield was followed by .2 meters of insulation and then the .8 meter magnet. For calculational purposes the magnet consisted of 60 percent aluminum, 30 percent copper, and 10 percent helium.

The first case resulted in the release of 18.9 MeV per 14 MeV neutron, an energy multiplication of 1.34. Sixty percent, or 11.3 MeV of the energy deposited was due to gamma interactions. Ten percent of the total energy was deposited in the reflector, and it is expected that this energy will be recoverable. Less than 1 percent of the energy was deposited in the shield. The tritium breeding ratio was 1.10.

In the second case a total of 18.0 MeV per 14 MeV neutron was deposited in the blanket and shield, an energy multiplication of 1.28. Since the breeding zone increases in thickness, the breeding ratio also increases to 1.18. The energy deposited from the neutron collisions and charged particle reactions increases from 7.60 MeV in the previous case to 8.23 MeV here, and is primarily related to the increased tritium production. The gamma energy deposited is 9.77 MeV, which decreases due to the reduction in capture gammas from lead, iron, and chromium since more neutrons are captured in lithium. This accounts for the reduction in energy multiplication from the previous case since about 7 MeV is released from a capture in lead, iron, or chromium as compared to 4.8 MeV released from a capture in Li^6. The results of these two cases are summarized in Table 1.



BLANKET SCHEMATIC

Figure 4

Table 1

Comparison of Blankets With and Without Reflector

Case 1 With Reflector

11.9 MeV Gamma Energy

7.6 MeV Neutron Energy

18.9 MeV Total Energy Deposited Per 14 MeV Neutron

1.34 Energy Multiplication

1.13 Tritium Breeding Ratio

Case 2 Without Reflector

9.77 MeV Gamma Energy

8.23 MeV Neutron Energy

18.0 MeV Total Energy Deposited Per 14 MeV Neutron

1.28 Energy Multiplication

1.18 Tritium Breeding Ratio

A more detailed analysis of the blanket/reflector/shield in case 1 was made and the results are listed in Table 2. Note that the 75 centimeter blanket was divided into three subzones for analysis.

Table 2

Tandem Mirror Neutronics Parameters

Total blanket	
Wall load MW/m^2 (normalized)	1
Tritium BR	
Li^6	1.107
Li^7	.024
Total	1.13
First Wall	
Radius (m)	1.1
Thickness (m)	.003
Composition	11 Cr-89 Fe
Power density W/cm^3	
Neutron	4.36
Gamma	3.91
Total	8.27
DPA per year	16.7
H production ppm/yr	477
He production ppm/yr	116
Wall load MW/m^2	1.
Breeding Blanket (Subzone 1)	
Thickness (m)	.247
Composition 10 v/o STR. 90 v/o breeder	
Structure Cr-11 Fe-89	
Breeding mat. Li-17 Pb-83	

Table 2 (cont.)

Power density W/cm^3	
Neutron	1.01
Gamma	1.82
Total	2.84
Breeding ratio	
Li^6	.506
Li^7	.022
Total	.528
Breeding Blanket (Subzone 2)	
Thickness (m)	.27
Composition 10 v/o STR. 90 v/o breeder	
(a) Structure Cr-11 Fe-12	
(b) Breeding material Li-17 Pb-83	
Power density W/cm^3	
Neutron	.44
Gamma	.31
Total	.75
Breeding ratio	
Li^6	.391
Li^7	.002
Total	.393
Breeding Blanket (Subzone 3)	
Thickness (m)	.23
Composition 10 v/o STR. 90 v/o breeder	
Structure Cr-11 Fe-12	

Table 2 (cont.)

Breeding material Li-17 Pb-83	
Power density W/cm^3	
Neutron	.21
Gamma	.13
Total	.34
Breeding ratio	
Li^6	.210
Li^7	.0001
Total	.21
Reflector	
Thickness	.25
Composition	
(a) Structure	95%
(b) Reflector FS: Fe-89 Cr-11	05%
(c) Coolant H_2O	
Power density W/cm^3	
(a) Neutron	.0089
(b) Gamma	.276
(c) Total	.285
Shield	
Thickness	.50
Composition	
B_4C	15 v/o %
Structure Cr-11 Fe-89	60 v/o %
Pb	15 v/o %

Table 2 (cont.)

H_2O	5 v/o %
Power density w/cm^3	
(a) Neutron	.0026
(b) Gamma	.0027
(c) Total	.0053
% total power	.43
Magnets	
Radius (m)	2.80
Thickness (m)	.80
Composition	
(a) Al	60 v/o
(b) Cu	30 v/o
(c) He	10 v/o
Power density (W/cm^3)	
(a) Neutron	9.67×10^{-8}
(b) Gamma	7.70×10^{-7}
(c) Total	$.867 \times 10^{-7}$
DPA YR	
(a) Al stabilizer - MAX	1.01×10^{-5}
(b) Cu stabilizer - MAX	6.00×10^{-6}

Radiation damage parameters in the first wall are listed. In addition the displacement per atom in the stabilizing material of the magnets was calculated. It may be seen that if the stabilizer was made of copper, then the magnets would have to be annealed about every two years. If the stabilizer was of aluminum, the 50 centimeter shield would not provide adequate protection.

Because of its high energy multiplication, we chose the blanket/reflector/shield combination in the first case as our base design from which we would more fully develop the concept. These ideas are explored in more detail in a following section after we have looked at shielding requirements, the headers, and blankets enriched in Li^6.

4. Shield Design

At one point we explored the idea of having only a small amount of shielding or none at all. This concept was precipitated by the idea that if the blanket were thick enough, perhaps it could be self-shielding due to the large amount of lead which would attenuate gammas and Li^6, with its high capture cross sections, would attenuate the neutrons. Under this concept the blanket would be simpler to design and complete energy recovery would be easier.

To explore this concept a series of transport calculations were made in which both the shield and blanket thicknesses were varied. The blanket was composed of a homogenized mixture of 10% steel and 90% $Li_{17}Pb_{83}$. The shield was a homogenized mixture of 60% ferritic steel, 15% lead, 15% B_4C and 5% H_2O.

Prior to looking at the shielding requirements, we wanted to insure that adequate tritium and energy multiplication could be obtained in this concept. In Figure 5 the tritium breeding ratio is plotted as a function of blanket

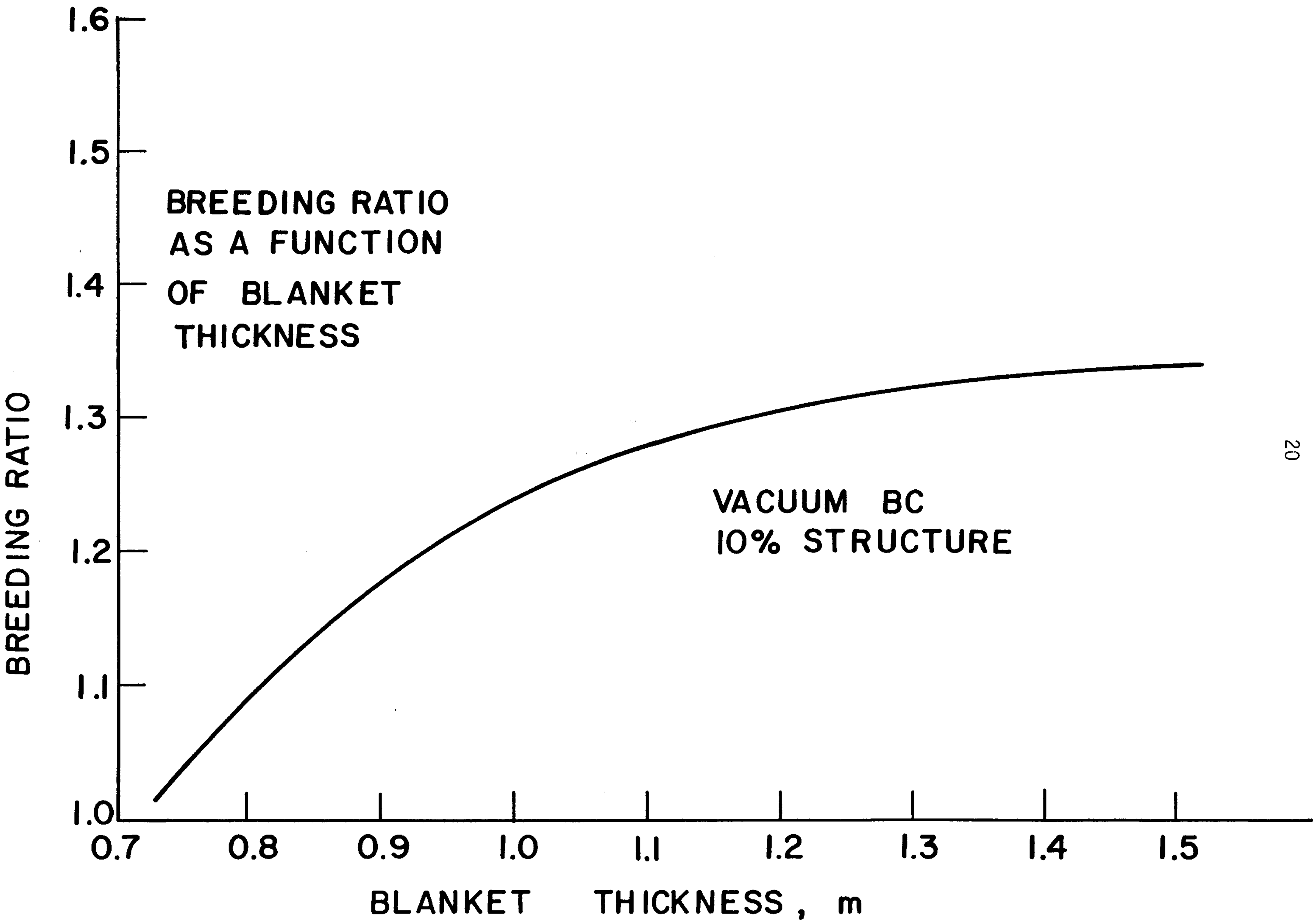

BREEDING RATIO
AS A FUNCTION
OF BLANKET
THICKNESS
VACUUM BC
10% STRUCTURE
BREEDING RATIO
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
BLANKET THICKNESS, m

Figure 5

thickness. In these calculations enough shield was added so that the total blanket and shield thickness was 1.5 meter. The result here is similar to that shown in Figure 3, and again it may be noted that adequate tritium may be obtained in rather thin blankets.

In Figure 6, the total energy deposited per 14 MeV neutron in the blanket and shield is plotted as a function of blanket thickness. Here also the total blanket and shield thickness was 1.5 meters. Note, however, that the total maximum energy released, ~ 18.5 MeV, is much less than that obtained with more structural material. Note also that if the blanket is thin, a considerable amount of energy would be lost in this configuration if a reflector is not employed.

The controlling parameter used to determine the shielding required is usually the dpa in the stabilizing material in the magnets. In Figure 7, we plotted the dpa/year in a copper stabilizer as a function of blanket and shield thickness for a 1 MW/m^2 neutron wall load. There were four blanket thicknesses: .70, .98, 1.24 and 1.36 meters. In Figure 7, the dpa/year is given as a function of thickness added to the blanket.

If a 50% resistivity increase corresponding to ~ 3×10^{-5} dpa in the copper stabilizer is taken as the limiting case, it may be seen that considerable shielding will be required if the magnets are to operate any reasonable time without annealing. These results indicate that shielding will be required and that the lithium lead blankets are quite transparent to neutrons. Later in the study when it was decided to use aluminum as the stabilizer, which is more susceptible to radiation damage than copper, we found that 60 cm of shield was necessary to protect the magnets.

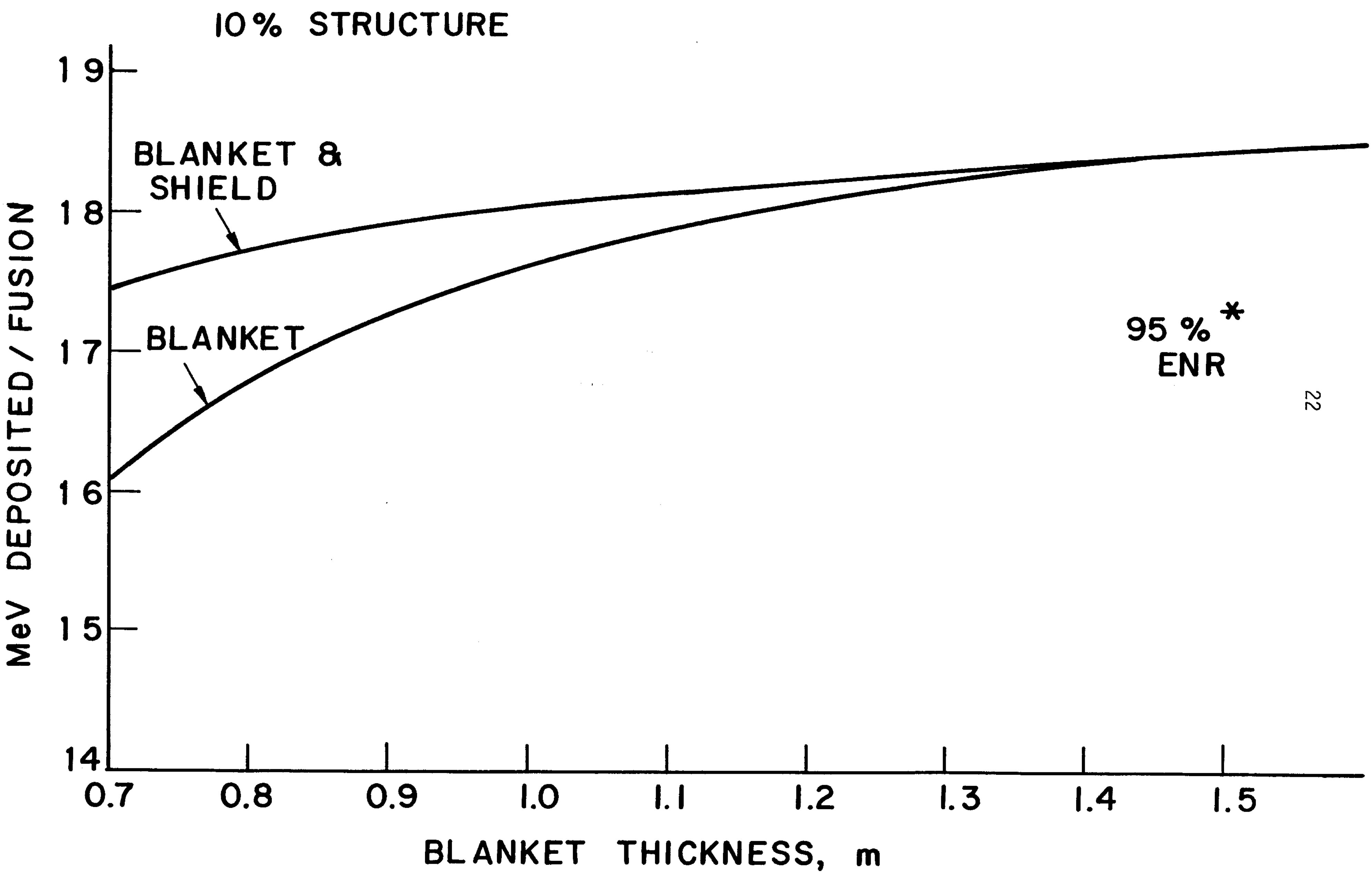

10% STRUCTURE
BLANKET & SHIELD
BLANKET
95 %* ENR
MeV DEPOSITED / FUSION
14
15
16
17
18
19
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
BLANKET THICKNESS, m

Figure 6

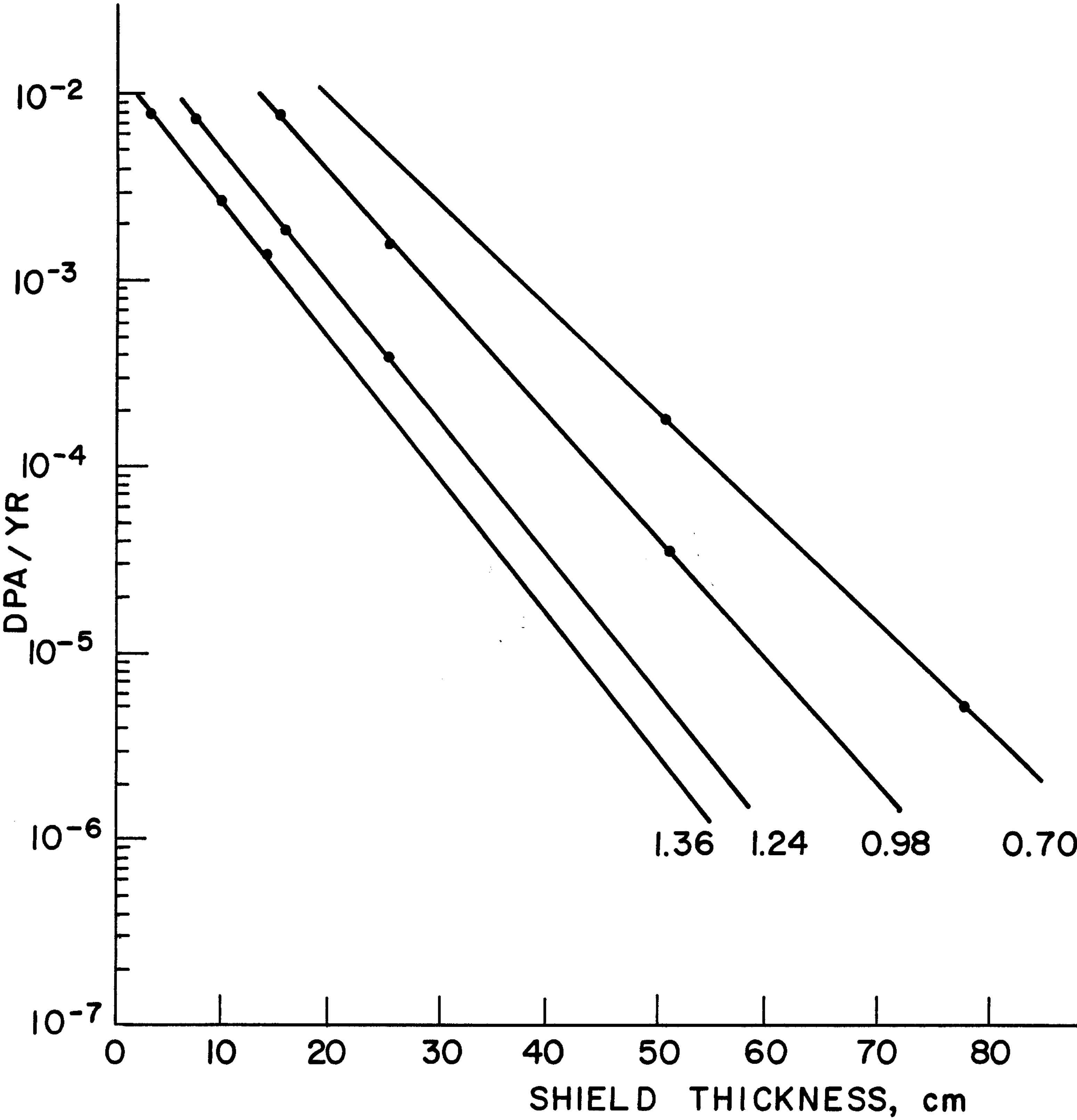


Figure 7

Dpa/year as a function of shield thickness added to the blanket.

5. Headers

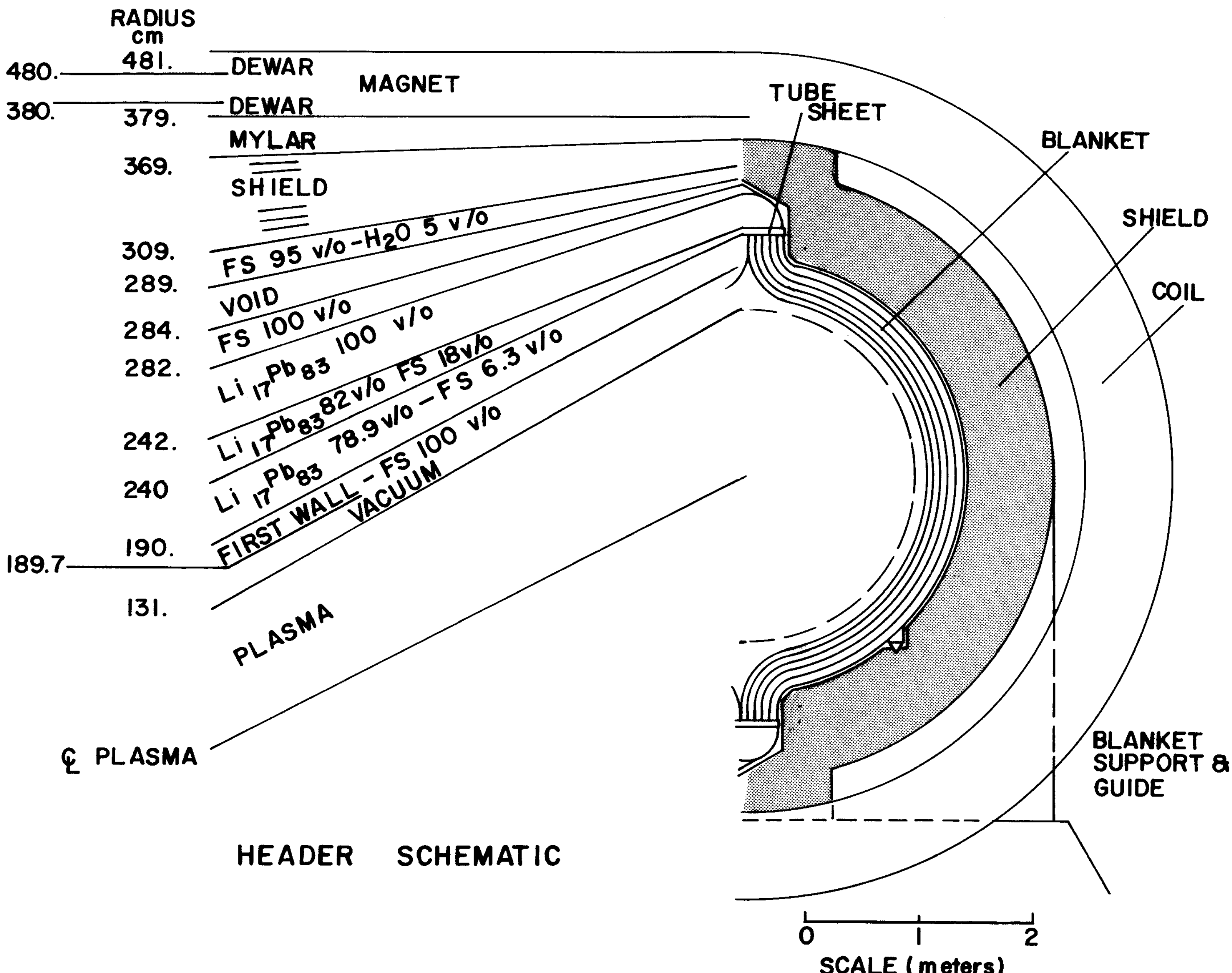
Since the headers present a different geometry to the 14 MeV neutrons than the midplane, we ran transport calculations with a geometrical model as shown in Figure 8. Here we assumed the magnets used aluminum stabilizer. We looked at several shield configurations and our final design was a 60 cm laminated shield containing 15% Pb, 55% ferritic steel, 3.6% water and 26.4% (.87 TD) B_4C.

We found that this shield configuration adequately protected the thermal insulation (mylar), electrical insulation (epoxy), and the aluminum stabilizer.

The maximum dpa in the aluminum was 6×10^{-7} dpa/yr per 1 MW/m^2 neutron wall load. The maximum radiation dose in the mylar was 1.6×10^6 rad/yr per 1 MW/m^2 neutron wall load.

6. Tritium Production

We found that tritium breeding ratios in excess of 1 were easily obtained in lithium-lead blankets. Since the lithium content is low, there is a greater probability that a high energy neutron will produce a (n,2n) or (n,3n) reaction in lead. These neutrons may be used for excess tritium production if some need exists elsewhere, i.e., startup of another plant. Under steady state conditions, however, it is unlikely that excess tritium will be needed, thus the excess neutrons can be used for energy multiplication by designing the blanket so that they will be captured in the structural material rather than in Li^6. Capture in the structure will release about 7 MeV as compared to $\sim$ 5 MeV in Li^6. Note that energy deposition in the blanket does not include the 3.5 MeV carried by the fusion alpha.



HEADER SCHEMATIC

Figure 8

We made several transport calculations to emphasize that large tritium breeding ratios could be obtained if necessary and to show that tritium production is at the expense of energy production.

The first transport calculation was made with a two meter blanket containing 100% $Li_{17}Pb_{83}$ with vacuum boundary conditions. The tritium breeding ratio was 1.73. This calculation was made to determine an approximate upper limit for tritium production.

Next we looked at two blankets, one enriched to 90% Li^6. The blankets were 75 cm thick and contained 90% $Li_{17}Pb_{83}$ and 10% structure. They were followed by 25 cm of ferritic steel reflector and 50 cm of shield. The enriched blanket had an energy deposition of 17.16 MeV and a breeding ratio of 1.59. The other blanket had an energy production of 18.9 MeV per 14 MeV neutron but the tritium breeding ratio drops to 1.13.

The blanket containing enriched lithium was extended to 100 cm thickness with a 25 cm reflector. The energy deposition in the blanket drops to 16.3 MeV; however, the tritium breeding ratio climbs to 1.64. In these examples it may be noted that large increases in energy production may be obtained by limiting tritium production.

7. Energy Multiplication

In the previous section it was noted that in a lithium-lead blanket, the energy multiplication is enhanced by low lithium content in the blanket by two means. First, there is a greater probability a high energy neutron collision will result in a (n,2n) or (n,3n) reaction in lead, and therefore, increased neutron production. Secondly, a neutron capture in the structural material or lead results in a greater energy release than if captured in lithium. In this section we explore this concept, and in addition look at more realistic blankets by allowing for void space in the blanket.

In Figure 1 it may seem that the blanket will be made of tubes and of course, voids will be between the tubes. If more structural material is desired, then the voids may be filled or conversely the tubes may be placed in lattices which fill the voids. We looked at several different blankets with varying amounts of void and increasing amounts of structural material as the distance from the plasma increases. Toward the plasma as little structural material as possible was used to promote (n,2n) and (n,3n) reactions in lead. Away from the plasma more structural material than was needed for support is used to promote the (n,γ) reactions. The zone usually referred to as the reflector is actually used for energy multiplication rather than reflection of neutrons, although this occurs.

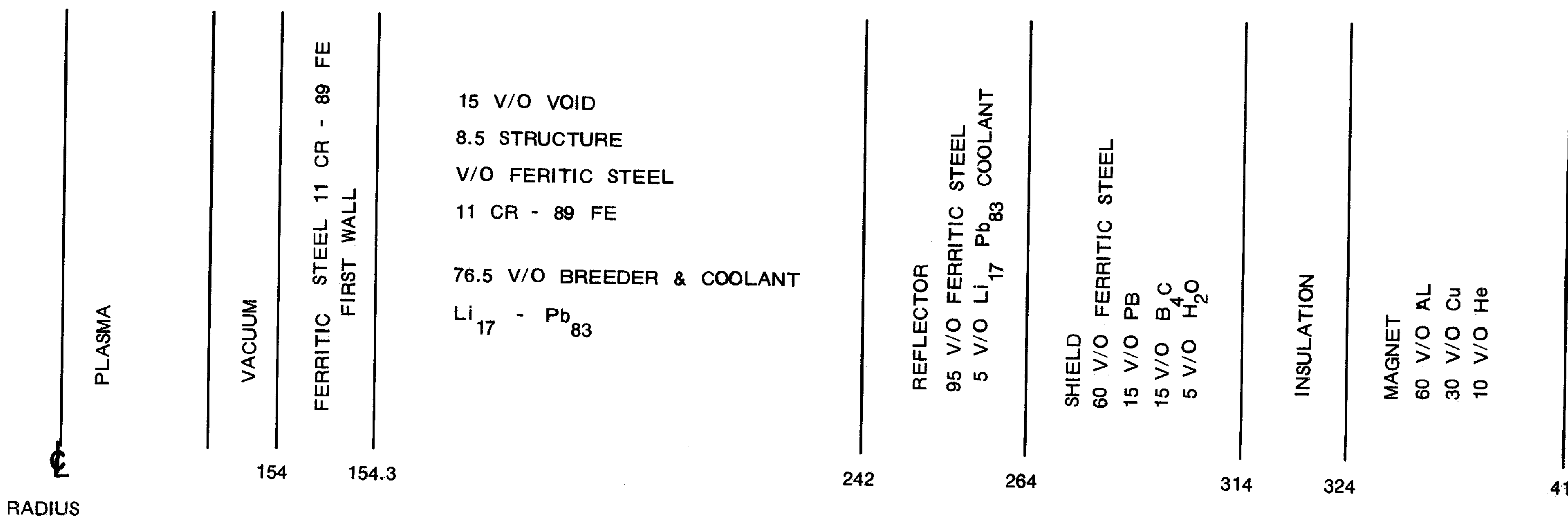
In Figure 9 a schematic of a blanket with a 15% void fraction is shown. Neutronic results for this blanket are given in Table 3 and a plot of the heating rates through the blanket is shown in Figure 10.

Next we varied the structural density across the blanket in a series of transport calculations. Examples of blanket configurations and results are given in Figure 11. Again it may be noted that the breeding ratio and energy deposition are strongly coupled.

These blanket configurations will form the basis for our final blanket design. The final design will take into consideration the final plasma and magnet radius, tritium breeding requirements and structural stability.

8. Conclusion

We have completed a series of parametric neutronic studies for a conceptual tandem mirror reactor. We found that the blanket of ferritic steel and



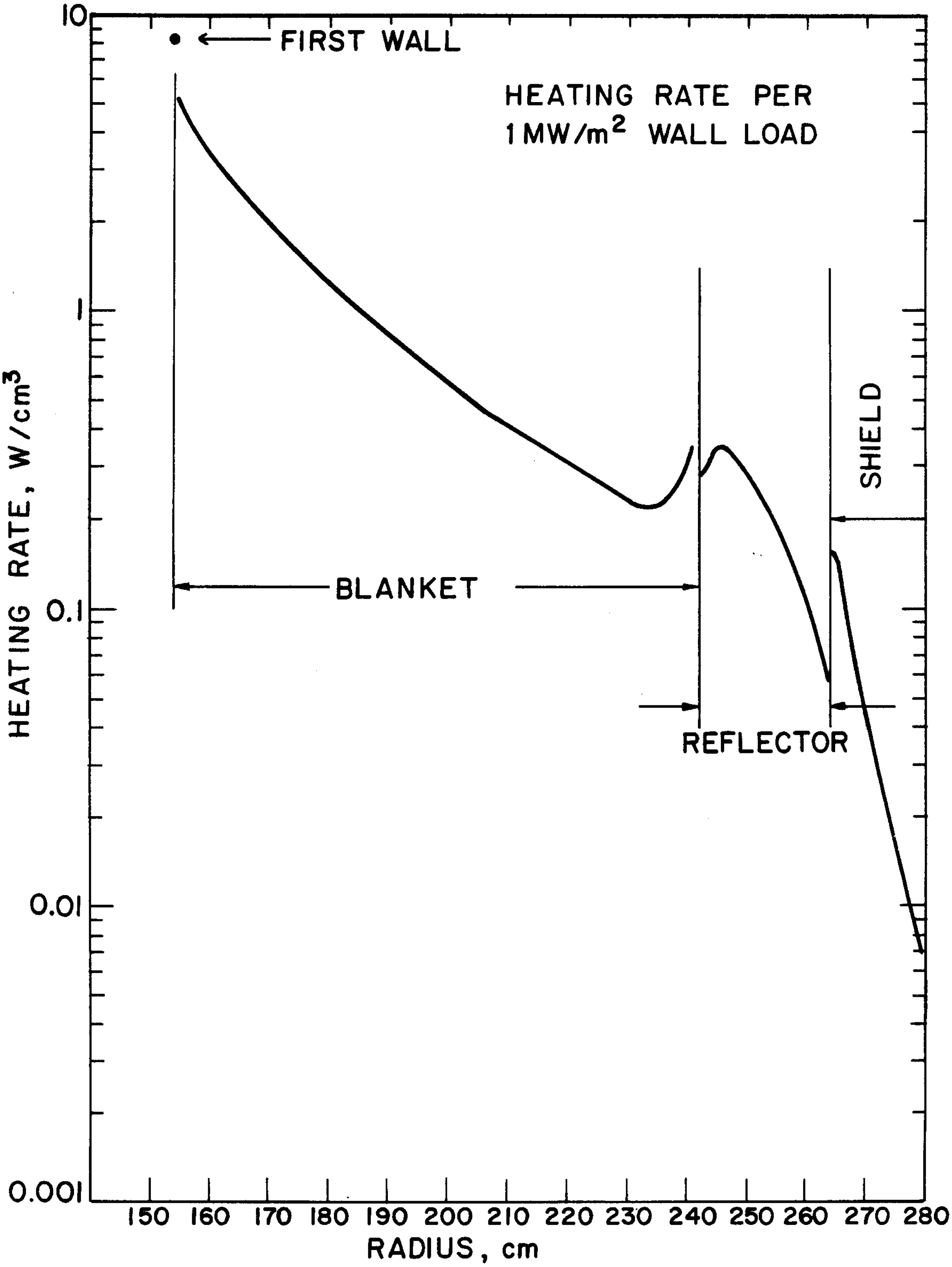
BLANKET SCHEMATIC - 15 % VOID IN BLANKET

FIG. 9

Table 3

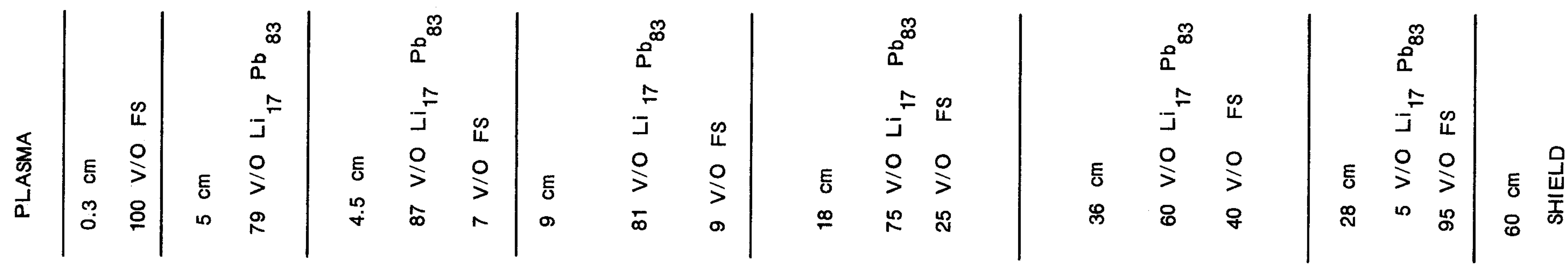
Neutronic Results for Blanket with 15 v/o Void

18.56	MeV Deposited per 14 MeV Neutron
1.3	Energy Multiplication
1.1	Breeding Ratio
1%	Energy Deposited in Shield

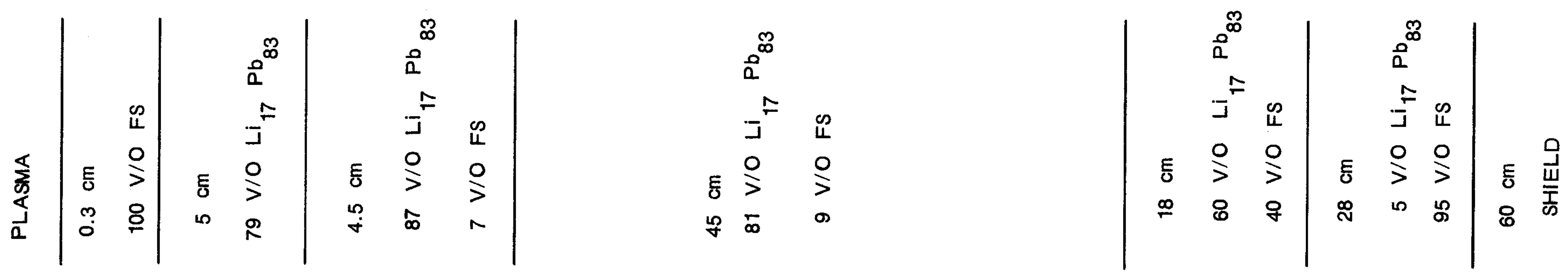


10
1
0.1
0.01
0.001
FIRST WALL
HEATING RATE PER
1 MW/m2 WALL LOAD
BLANKET
REFLECTOR
SHIELD
HEATING RATE, W/cm3
150 160 170 180 190 200 210 220 230 240 250 260 270 280
RADIUS, cm

Fig. 10

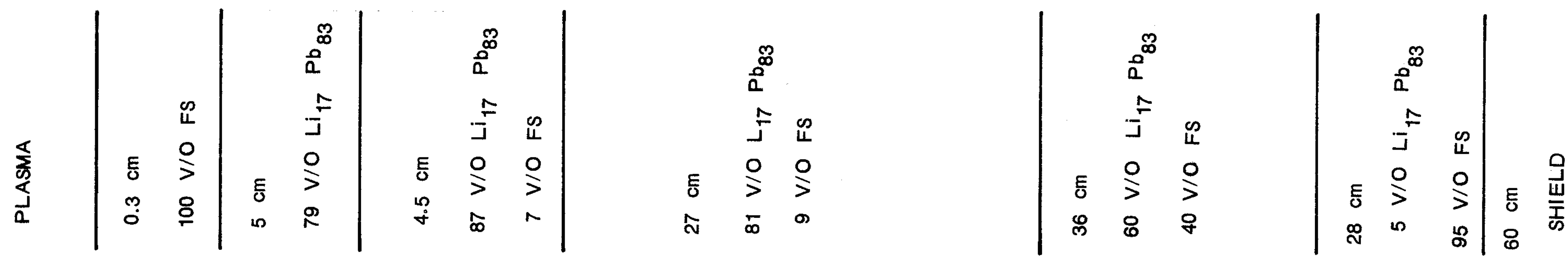


CASE 1 ENERGY DEPOSITED 19.48 MeV - TRITIUM B. R. 1.04

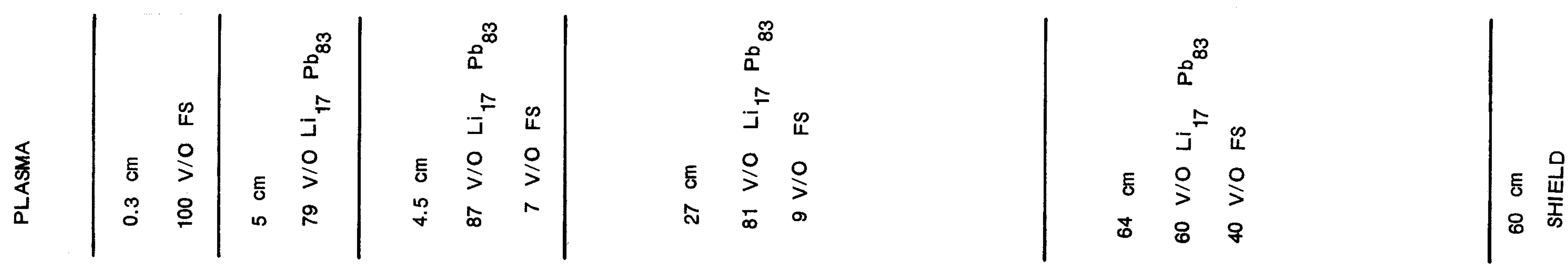


CASE 2 ENERGY DEPOSITED 19.17 MeV - TRITIUM B. R. 1.10

FIG. 11 EXAMPLE BLANKET CONFIGURATIONS



CASE 3 ENERGY DEPOSITED 19.42 MeV - TRITIUM B.R. 1.04



CASE 4 ENERGY DEPOSITED 19.17 MeV - TRITIUM B. R. 1.1

FIGURE 11. (CONTD.) EXAMPLE BLANKET CONFIGURATIONS.

lithium-lead meet our design criteria. In addition, through design and material selection, high energy multiplication, which enhances the economics of the system, may be obtained.

References

1. B. Badger, et al., "Preliminary Information on the University of Wisconsin Tandem Mirror Reactor Design", UWFDM-325, University of Wisconsin (Nov. 1979).

2. W. W. Engle, Jr., "ANISN, A 1-D Discrete Ordinates Transport Code with Anistropic Scattering", ORNL K 1693 (1973).

3. RSIC Data Library Collection, "Vitamic-C, 171 Neutron, 36 Gamma-Ray Group Cross Section Library in AMPX Interface Format for Fusion Neutronics Studies", DLC-41, ORNL.

4. RSIC Data Library Collection, "MACKLIB-IV, 171 Neutron, 36 Gamma-Ray Group Kerma Factor Library", DLC-60, ORNL.

Part II

Neutronic Design Study of WITAMIR-I

Presented at the Eleventh Symposium on Fusion Technology
Oxford, England - Sept. 1980

1. Abstract - Published in Abstracts of Papers, Presented at the Eleventh Symposium on Fusion Technology, Sept. 1980.

NEUTRONIC DESIGN STUDY OF WITAMIR-I

R.T. Perry C.W. Maynard
University of Wisconsin

In this paper, we discuss a neutronic design study of a fusion reactor blanket, shield, and magnet which utilizes a eutectic mixture of lithium and lead as the coolant and tritium breeding material. These calculations were made as a part of a conceptual design study of a tandem mirror reactor, WITAMIR-I, at the University of Wisconsin.

The blanket consists of a series of tube banks, 72.5 cm thick, made of the ferritic steel, HT-9, running circumferentially around the plasma reaction chamber. A eutectic mixture of $Li_{17}Pb_{83}$ flows through the tubes to provide cooling and tritium breeding. The tube bank is followed by a 28 cm, water cooled, ferritic steel reflector, and the energy deposition in the reflector is sufficient to warrant utilization. Next is a 60 cm shield, which is followed by thermal insulation and the magnets. The magnets are 100 cm thick and have an aluminum structure and stabilizer.

The results of our calculations show that we have achieved exceptionally high energy multiplication in the blanket. A total of 19.34 MeV is deposited in the blanket per 14 MeV neutron incident on the first wall. The blanket has a tritium breeding ratio of 1.08.

The high energy multiplication is achieved by utilizing the high (n,2n) and (n,3n) reaction probabilities in lead and promoting, by design, the resultant neutron captures in the structural material which releases about 7 MeV per capture. This is accomplished by keeping the structural material toward the plasma to a minimum and using the low lithium percent eutectic mixture. Into the blanket, however, the percent structure is increased, in fact by far more than is actually needed for support, in order to increase the probability of a capture in the structure rather than in ^{6}Li which releases only about 5 MeV per capture.

The blanket and especially the first wall are subject to intense high energy neutron bombardment. Therefore, as a measure of the damage expected, we have calculated the dpa, hydrogen production, and helium production in the structural material. The first wall radiation damage parameters per year per MW/m^2 wall load are 15.1 dpa, 101 ppm He production, and 478 ppm hydrogen production.

The blanket is somewhat transparent to neutrons, as compared to other designs. Thus, our calculations indicate that 60 cm of shielding is required to adequately protect the magnet stabilizer, epoxy, and insulation from excessive radiation damage when the reactor has a first wall load of 2.4 MW/m^2.

In conclusion, we note that this combination of lithium-lead and ferritic steel meet all our neutronic design criteria. In addition, the blanket's high energy multiplication enhances the economics of the system.

AUTHORS' NOTE: The parameters calculated and presented in this abstract were based on a first wall radius of 1.54 meters. The final design had a first wall radius of .967 meters. The original abstract also contains a mistake. The hydrogen production was given as 378 ppm. It should have been 478 ppm. It has been corrected here.

2. Text of Paper Published in
Proceedings of the Eleventh
Symposium on Fusion Technology

NEUTRONIC DESIGN STUDY OF WITAMIR-I

C.W. Maynard, R.T. Perry
University of Wisconsin

ABSTRACT

A neutronic design study of a fusion reactor blanket shield and magnet which utilizes a eutectic mixture of lithium and lead as the coolant and tritium breeding material and ferritic steel as the structural material is presented. These calculations were made as part of a conceptual design study of a tandem mirror reactor, WITAMIR-I, at the University of Wisconsin. The results of our calculations show that 19.3 MeV is deposited in the blanket per 14 MeV neutron, which results in an exceptionally high energy multiplication. In addition this blanket has a tritium breeding ratio of 1.07, and the radiation damage to the structural material and magnets are within design limits.

1. INTRODUCTION

In this paper we present the neutronic analysis of the central cell blanket and shield of WITAMIR-I, a tandem mirror reactor. This analysis is part of a conceptual design study at the University of Wisconsin. The results and design parameters for WITAMIR-I are discussed in detail elsewhere [1].

The blanket for this reactor will consist of a series of tube banks made of the ferritic steel, HT-9, running circumferentially around the plasma reaction chamber. A eutectic mixture of $Li_{17}Pb_{83}$ flows through the tubes to provide cooling and tritium production. The tube bank is followed by a water cooled reflector, and energy deposition is sufficient to warrant utilization. A sixty centimeter shield is followed by insulation and then the magnets. A cross sectional view of the reactor is shown in Figure 1.

The primary neutronic design requirements for the blanket and shield unit are:

- It must breed tritium.
- It must convert the kinetic energy of the fusion reaction into heat.
- It must attenuate the flux and provide adequate protection for the magnets and other equipment against radiation and heat.
- It must be resistant to radiation damage.

These requirements are absolutely essential for the design of a viable blanket and shield and are also subject to economic and environmental constraints. There are many secondary features which are not absolutely essential but would be desirable. These features include:

- Low blanket and shield activity.
- High blanket energy multiplication.

The TMR blanket and shield, shown in Figure 2, meet the basic requirements. In addition we have achieved a high blanket energy multiplication through material selection and design. In the following sections, these and other neutronic design parameters will be discussed.

2. METHODOLOGY AND DATA

The neutronic and photonic calculations were made with the one-dimensional code ANISN [2]. A P3-S8 approximation in cylindrical geometry was used in the transport calculation. The transport cross sections were a coupled 25 neutron-21 gamma group data library created from the RSIC DLC-41B/Vitamin C Data Library [3]. Kerma factors, helium and hydrogen

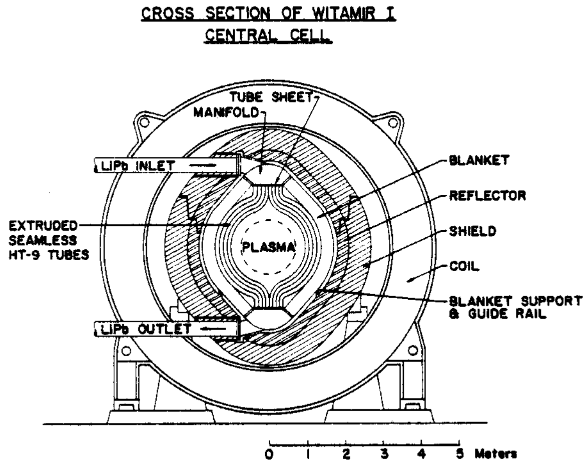
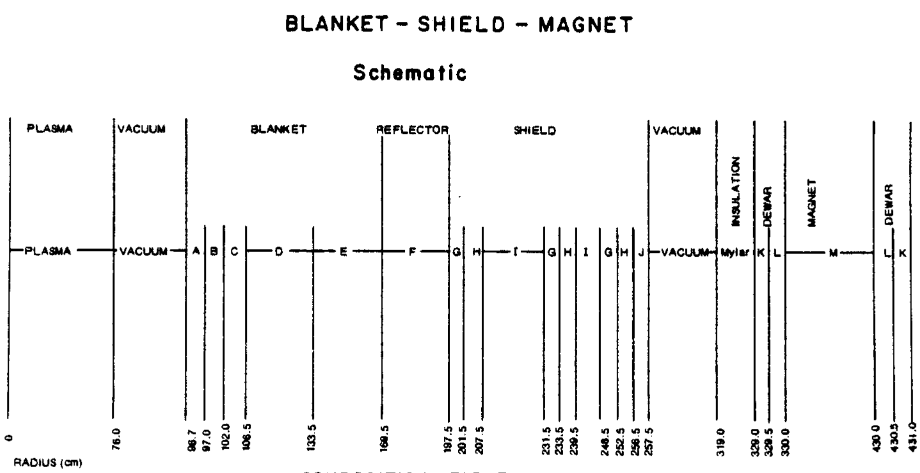


Fig. 1

production cross sections and displacement cross sections were created from the DLC-60/MACKLIB-IV Data Library [4]. A standard CTR weighting function was used to collapse the DLC-60 and DLC-41B libraries into the 25 neutron and 21 gamma energy group structures.

The calculational model of the blanket, shield and magnet is shown in Figure 2. Note that the TMR, because it is basically a long cylinder, lends itself well to 1-D cylindrical modelling. The tube banks overlap, and therefore they



COMPOSITION TABLE

A - 100 % FERRITIC STEEL (HT - 9)
B - 79 % $Li_{17}Pb_{83}$
C - 84 % $Li_{17}Pb_{83}$, 7 % FERRITIC STEEL (F.S.)
D - 81 % $Li_{17}Pb_{83}$, 9 % F.S.
E - 75 % $Li_{17}Pb_{83}$, 25 % F.S.
F - 5 % H_2O, 95 % F.S.
G - 90 % Pb, 5 % H_2O, 5 % F.S.
H - 87 % B_4C
I - 95 % F.S., 5 % H_2O
J - 100 % F.S.
K - 100 % Al 2219
L - 100 % He
M - 17.8 % Al, 69 % Al 2219, 4 % He, 9.2 % INSULATION

Fig. 2

are essentially a homogeneous zone, again simplifying modelling. Thus, for the central cell of the TMR, it was felt that 2 or 3-D modelling was not needed, as is often the case for other conceptual designs with their toroidal or more complicated geometry. We did take into consideration the headers, which present a different geometry to the 14 MeV neutrons. We ran several cases with models which we felt adequately described this geometry to insure that the magnets in these regions were adequately protected.

3. ENERGY DEPOSITION AND TRITIUM BREEDING

The blanket and shield compositions and structure were chosen following parameter studies [5] in which blanket thickness, percent structure and lithium enrichment were varied. We found that the energy multiplication increased with increasing volume percent of structure. Since large energy multiplication is highly desirable from an economic point of view, it was a major consideration in our parameter studies. Basically, our final design was one in which we had maximized structural material consistent with adequate tritium breeding, magnetic protection and geometrical requirements.

The energy multiplication for this blanket is 1.37. The energy multiplication is defined as the ratio of the energy deposited in the blanket to that carried by the fusion neutron, 14.06 MeV. In Table 1, the energy multiplication for several other reactors is given. Note that the energy multiplication for WITAMIR-I is significantly greater than the other conceptual designs. These numbers do not take into account the 3.52 MeV carried by the fusion alpha particle. It is interesting to compare the wall loads between the designs which, with the exception of WITAMIR-I, are tokamaks. From them one can see that the power densities and structural radiation damage will not be greatly different between tokamaks and TMRs.

TABLE I

Energy Multiplication and Wall Loads for Various Fusion Reactor Conceptual Designs

	Energy Multiplication	Wall Load MW/m^2
UWMAK-I [6]	1.17	1.25
UWMAK-II [7]	1.28	1.16
UWMAK-III [8]	1.29	2.5
NUWMAK [9]	1.22	4.0
WITAMIR-I	1.37	2.4

In this blanket, the energy multiplication is enhanced by the low lithium content of the blanket in two ways. First, there is a greater probability of a high energy neutron collision in lead which can result in an (n,2n) or (n,3n) reaction. Lead has large cross sections for these reactions, thus, decreasing the lithium content increases neutron production. Secondly, a neutron capture in the structural material or lead will release about 7 MeV as compared to a capture in ^6Li which releases about 5 MeV.

We designed the blanket to take advantage of these processes. Toward the plasma, the structural material is kept to a minimum to enhance the (n,2n) and (n,3n) reactions in lead. Into the blanket, however, the percent of structural material is increased, in fact by far more than is actually needed structurally. This was done to suppress the captures in ^6Li, and enhance the captures in the steel. In this blanket the zone usually referred to as a reflector is used to enhance the energy multiplication through neutron capture, rather than reflecting neutrons back into the active blanket, although this occurs.

In Table II the energy deposited per zone per 14 MeV neutron is given. Note that the gamma energy released is larger than the neutron energy indicating large neutron capture in the lead and structure. This blanket has a tritium breeding ratio of 1.07. To emphasize the point that increases in the tritium breeding ratio reduce the energy multiplication, we enriched the lithium in a blanket to 95% ^6Li. The tritium breeding ratio increased to 1.6; however, the total energy production dropped to 16.4 MeV per 14 MeV neutron.

In Figure 3, the heating rates in the blanket are shown. These results are for a one MW/m^2 wall load and may be scaled to any desired value. The reflector generates 9.9% of the total energy and most of that energy is from gamma interactions.

The shield, which consists of several layers of ferritic steel, B_4C and lead, is water cooled. About 3/10 of 1 percent of the total energy is deposited in the shield.

TABLE II

Energy Deposited by Zone Per 14 MeV Neutron -MeV-

	Gamma	Neutron	Total
First Wall	.15	.19	.34
Blanket	10.17	6.90	17.07
Reflector	1.86	.06	1.92
Shield	.0017	.0012	.0029

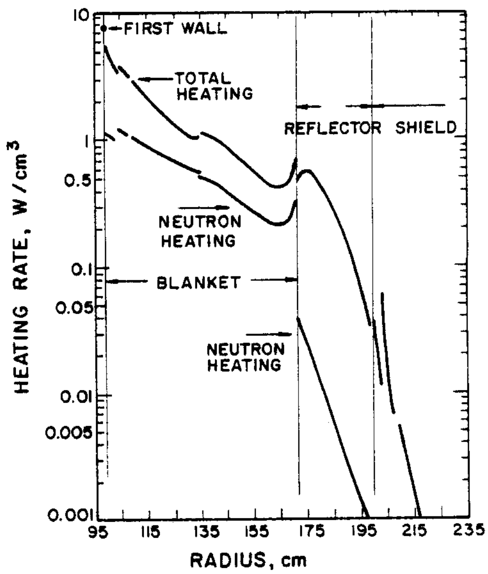


Fig. 3 Heating rates in blanket

4. STRUCTURAL RADIATION DAMAGE

The blanket, and especially the first wall, are subject to intense high energy neutron bombardment. A measure of the damage expected is the number of displacements per atom of structural material. In addition, helium and hydrogen production in the structural material through various neutron reactions also lead to material degeneration. In Table III, the displacements per atom, helium production and hydrogen production in the first wall are given. These results are for one MW/m^2 year of continuous operation. In Figure 4 a plot of the displacement per atom in the structural material through the blanket is shown.

TABLE III

First Wall Radiation Damage Parameters Per Yr: 1 MW/m^2 Wall Load

Displacement Per Atom	16.88
He Production ppm	117
Hydrogen Production ppm	482

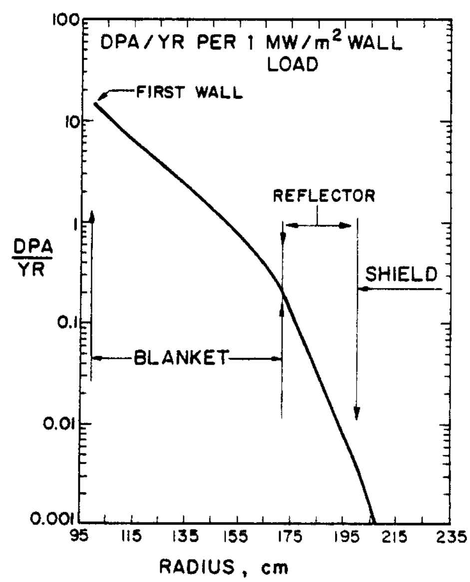


Fig. 4 Displacement per atom in blanket

5. MAGNET SHIELDING

The function of the shield is to protect the magnets from heat and radiation. Unfortunately, the blanket is a poor attenuator of neutrons, primarily due to the large volume percent of lead which is relatively transparent to neutrons. Thus, a 60 cm shield was required for adequate protection.

The neutron fluence in the superconductors primarily affects the stabilizing material and results in an increase of the electrical resistivity. The increase in resistivity is related to the number of displacements per atom in the stabilizer, which in our design is aluminum. The increase in resistivity limits the magnet functions; however, complete recovery of the magnet is possible by annealing.

A design limit of two years of operation without annealing was set. It is expected that annealing would be required when a resistivity increase of 50% occurred.

This corresponds to 4×10^{-6} dpa.

Taking the maximum value of the dpa in aluminum, which occurs at the edge, scaling it to 2.4 MW/m^2 wall load for a two year period results in a value of 1.3×10^{-6} which is well within the design limits. Similar results were found at the top and bottom of the reactor where a different blanket model was used to simulate the headers.

The radiation effects on the epoxy and thermal insulation used in the magnets are not reversible. Thus, it is important that these last for the life of the reactor. The limits would be about 1×10^{10} rads for the thermal insulation and $1 - 5 \times 10^9$ rads for the epoxy. Our calculations indicate that a maximum dose of 1.6×10^6 rads per year per MW/m^2 wall load will occur in the thermal insulation at the headers, and 8.6×10^6 rads at the midplane. For the epoxy a dose of 1.5×10^6 rads per MW/m^2 per year will occur at the headers and 6.4×10^5 rads at the midplane. Even at full power for thirty years, these would be within limits.

6. CONCLUSION

The blanket and shield for the TMR meet all of our basic design criteria. The blanket has a tritium breeding ratio of 1.07 and the shield adequately protects the magnets. In addition, the blanket has exceptionally high energy multiplication which enhances the economics of the system.

7. ACKNOWLEDGEMENTS

Financial support for this research has been provided by the U.S. Department of Energy through the Office of Fusion Energy.

8. REFERENCES

[1] SANTARIUS, J.F., et al., WITAMIR-I, A Tandem Mirror Reactor With Non-Zero Nu", Eleventh Symposium on Fusion Technology, Oxford (Sept. 1980).

[2] ENGLE, W.W., Jr., "ANISN, A 1-D Discrete Ordinates Transport Code With Anisotropic Scattering", ORNL K 1693 (1973).

[3] RSIC Data Library Collection, "Vitamin-C, 171 Neutron, 36 Gamma-Ray Group Cross Section Library in AMPX Interface Format for Fusion Neutronics Studies", DLC-41, ORNL.

[4] RSIC Data Library Collection, "MACKLIB-IV, 171 Neutron, 36 Gamma-Ray Group Kerma Factor Library, DLC-60, ORNL.

[5] PERRY, R.T. and C.W. MAYNARD, "A Neutronic Study of a Lithium Lead Cooled Tandem Mirror Reactor Blanket", Transactions ANS, Volume 34, Las Vegas (June 1980).

[6] BADGER, B., et al., "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design", UWFDM-68, University of Wisconsin (1973).

[7] BADGER, B., et al., "UWMAK-II, A Conceptual Tokamak Power Reactor Design", UWFDM-112, University of Wisconsin (1975).

[8] BADGER, B., et al., "UWMAK-III, A Non-circular Tokamak Power Reactor Design", EPRI ER-368, EPRI (1976).

[9] BADGER, B., et al., "NUWMAK, A Tokamak Reactor Design Study", UWFDM-330, University of Wisconsin (1979).

3. Viewgraphs Presented at the
Eleventh Symposium on Fusion
Technology - Oxford - Sept. 1980

NEUTRONIC DESIGN STUDY
OF WITAMIR-I

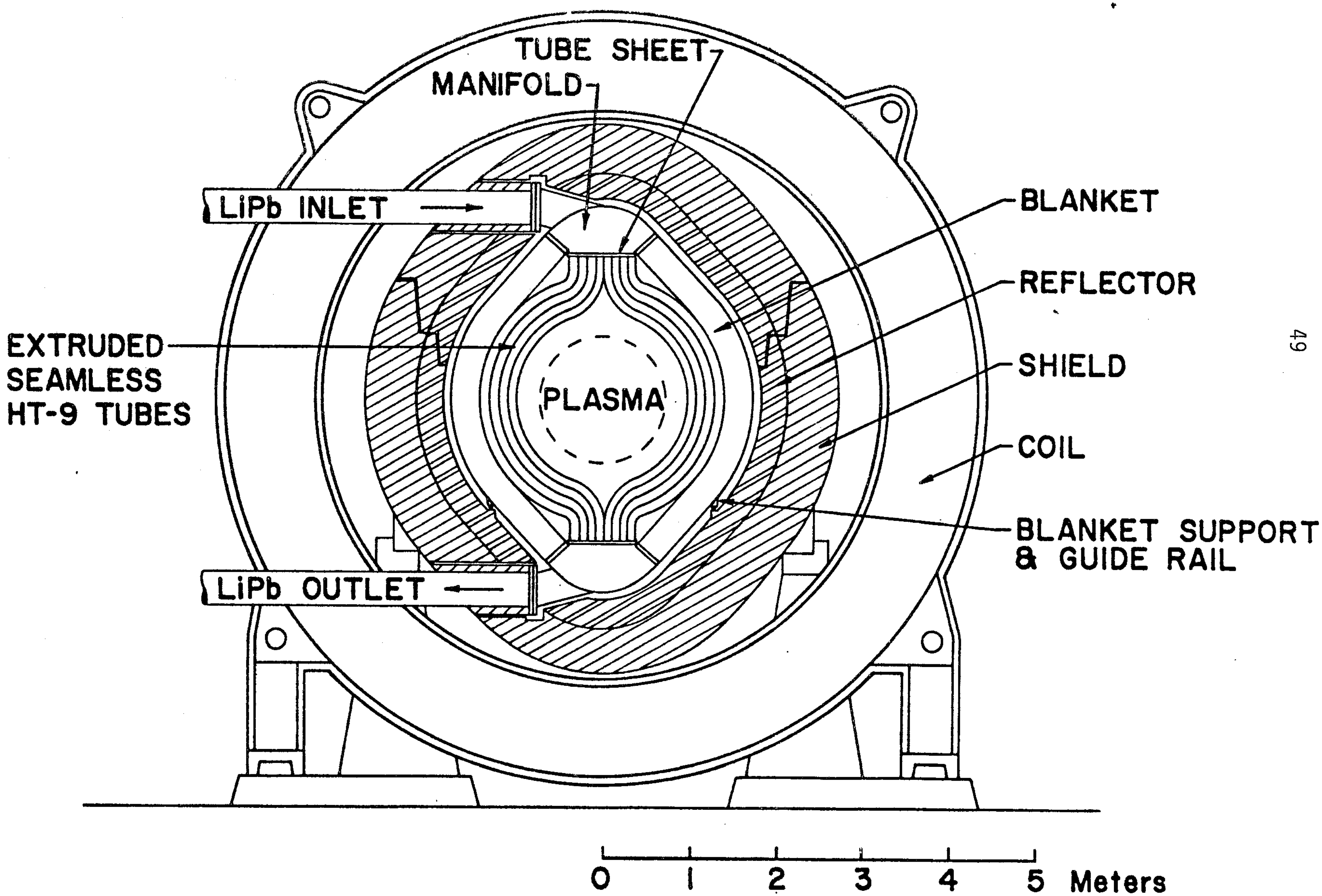
C.W. MAYNARD, R.T. PERRY
UNIVERSITY OF WISCONSIN

ABSTRACT

A NEUTRONIC DESIGN STUDY OF A FUSION REACTOR BLANKET, SHIELD AND MAGNET WHICH UTILIZES A EUTECTIC MIXTURE OF LITHIUM AND LEAD AS THE COOLANT AND TRITIUM BREEDING MATERIAL AND FERRITIC STEEL AS THE STRUCTURAL MATERIAL IS PRESENTED. THESE CALCULATIONS WERE MADE AS PART OF A CONCEPTUAL DESIGN STUDY OF A TANDEM MIRROR REACTOR, WITAMIR-I, AT THE UNIVERSITY OF WISCONSIN. THE RESULTS OF OUR CALCULATIONS SHOW THAT 19.3 MeV IS DEPOSITED IN THE BLANKET PER 14 MeV NEUTRON, WHICH RESULTS IN AN EXCEPTIONALLY HIGH ENERGY MULTIPLICATION.

THE BLANKET FOR THIS REACTOR WILL CONSIST OF A SERIES OF TUBE BANKS MADE OF THE FERRITIC STEEL, HT-9, RUNNING CIRCUMFERENTIALLY AROUND THE PLASMA REACTION CHAMBER. A EUTECTIC MIXTURE OF $Li_{17}Pb_{83}$ FLOWS THROUGH THE TUBES TO PROVIDE COOLING AND TRITIUM PRODUCTION. THE TUBE BANK IS FOLLOWED BY A WATER COOLED REFLECTOR, AND ENERGY DEPOSITION IS SUFFICIENT TO WARRANT UTILIZATION. A SIXTY CENTIMETER SHIELD IS FOLLOWED BY INSULATION AND THEN THE MAGNETS.

CROSS SECTION OF WITAMIR I
CENTRAL CELL

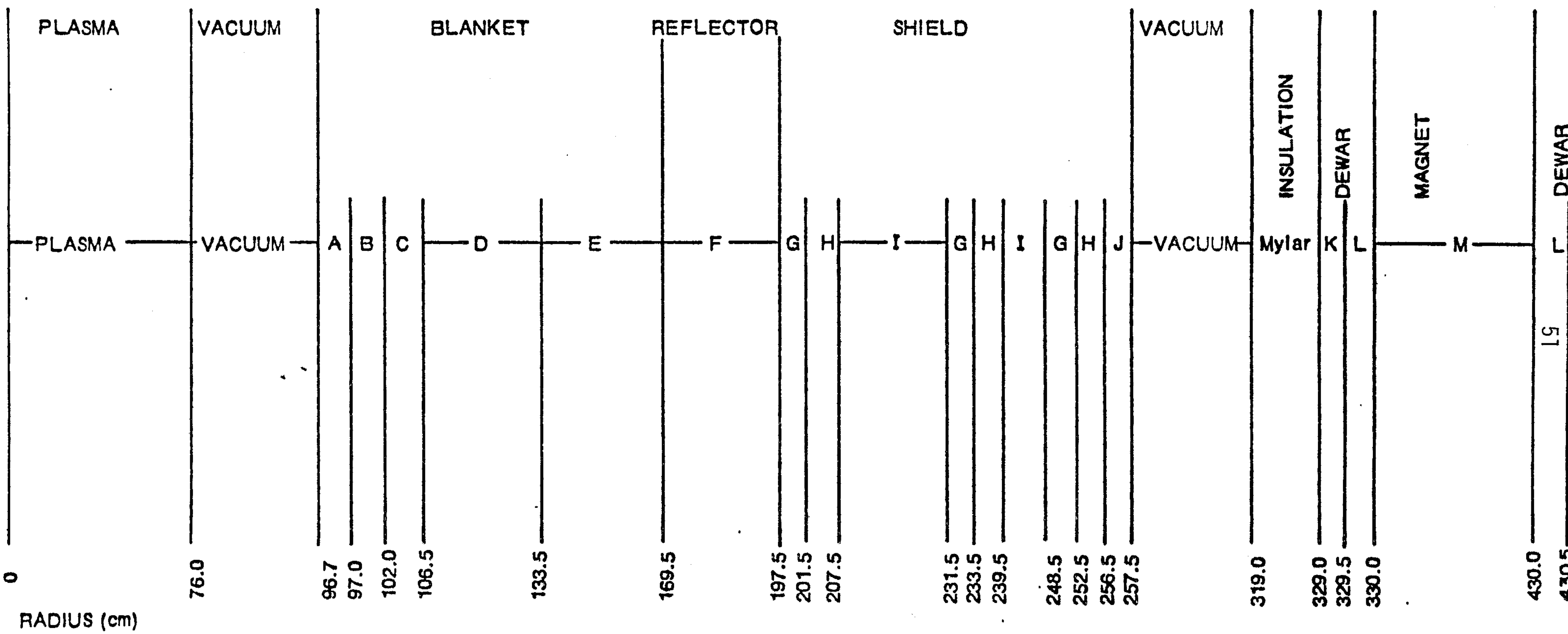


METHODOLOGY AND DATA

THE NEUTRONIC AND PHOTONIC CALCULATIONS WERE MADE WITH THE ONE-DIMENSIONAL CODE ANISN. A P3-S8 APPROXIMATION IN CYLINDRICAL GEOMETRY WAS USED IN THE TRANSPORT CALCULATION. THE TRANSPORT CROSS SECTIONS WERE A COUPLED 25 NEUTRON-21 GAMMA GROUP DATA LIBRARY CREATED FROM THE RSIC DLC-41B/VITAMIN-C DATA LIBRARY. KERMA FACTORS, HELIUM AND HYDROGEN PRODUCTION CROSS SECTIONS AND DISPLACEMENT CROSS SECTIONS WERE CREATED FROM THE DLC-60/ MACKLIB-IV DATA LIBRARY. A STANDARD CTR WEIGHTING FUNCTION WAS USED TO COLLAPSE THE DLC-60 AND DLC-41B LIBRARIES INTO THE 25 NEUTRON AND 21 GAMMA ENERGY GROUP STRUCTURE.

BLANKET - SHIELD - MAGNET

Schematic



COMPOSITION TABLE

A - 100 % FERRITIC STEEL (HT - 9)

B - 79 % $Li_{17}Pb_{83}$

C - 84 % $Li_{17}Pb_{83}$, 7 % FERRITIC STEEL (F.S.)

D - 81 % $Li_{17}Pb_{83}$, 9 % F.S.

E - 75 % $Li_{17}Pb_{83}$, 25 % F.S.

F - 5 % H_2O, 95 % F.S.

G - 90 % Pb, 5 % H_2O, 5 % F.S.

H - 87 % B_4C

I - 95 % F.S., 5 % H_2O

J - 100 % F.S.

K - 100 % Al 2219

L - 100 % He

M - 17.8 % Al, 69 % Al 2219, 4 % He, 9.2 % INSULATION

ENERGY MULTIPLICATION AND WALL LOADS FOR VARIOUS FUSION REACTOR CONCEPTUAL DESIGNS

	ENERGY MULTIPLICATION	WALL LOAD MW/M^2
UWMAK-I	1.17	1.25
UWMAK-II	1.28	1.16
UWMAK-III	1.29	2.5
NUWMAK	1.22	4.0
WITAMIR-I	1.37	2.4

IN THIS BLANKET THE ENERGY MULTIPLICATION IS ENHANCED BY THE LOW LITHIUM CONTENT OF THE BLANKET IN TWO WAYS. FIRST, THERE IS A GREATER PROBABILITY OF A HIGH ENERGY NEUTRON COLLISION IN LEAD WHICH CAN RESULT IN AN (N,2N) OR (N,3N) REACTION. LEAD HAS LARGE CROSS SECTIONS FOR THESE REACTIONS, THUS, DECREASING THE LITHIUM CONTENT INCREASES NEUTRON PRODUCTION. SECONDLY, A NEUTRON CAPTURE IN THE STRUCTURAL MATERIAL OR LEAD WILL RELEASE ABOUT 7 MEV AS COMPARED TO A CAPTURE IN ^{6}LI WHICH RELEASES ABOUT 5 MEV.

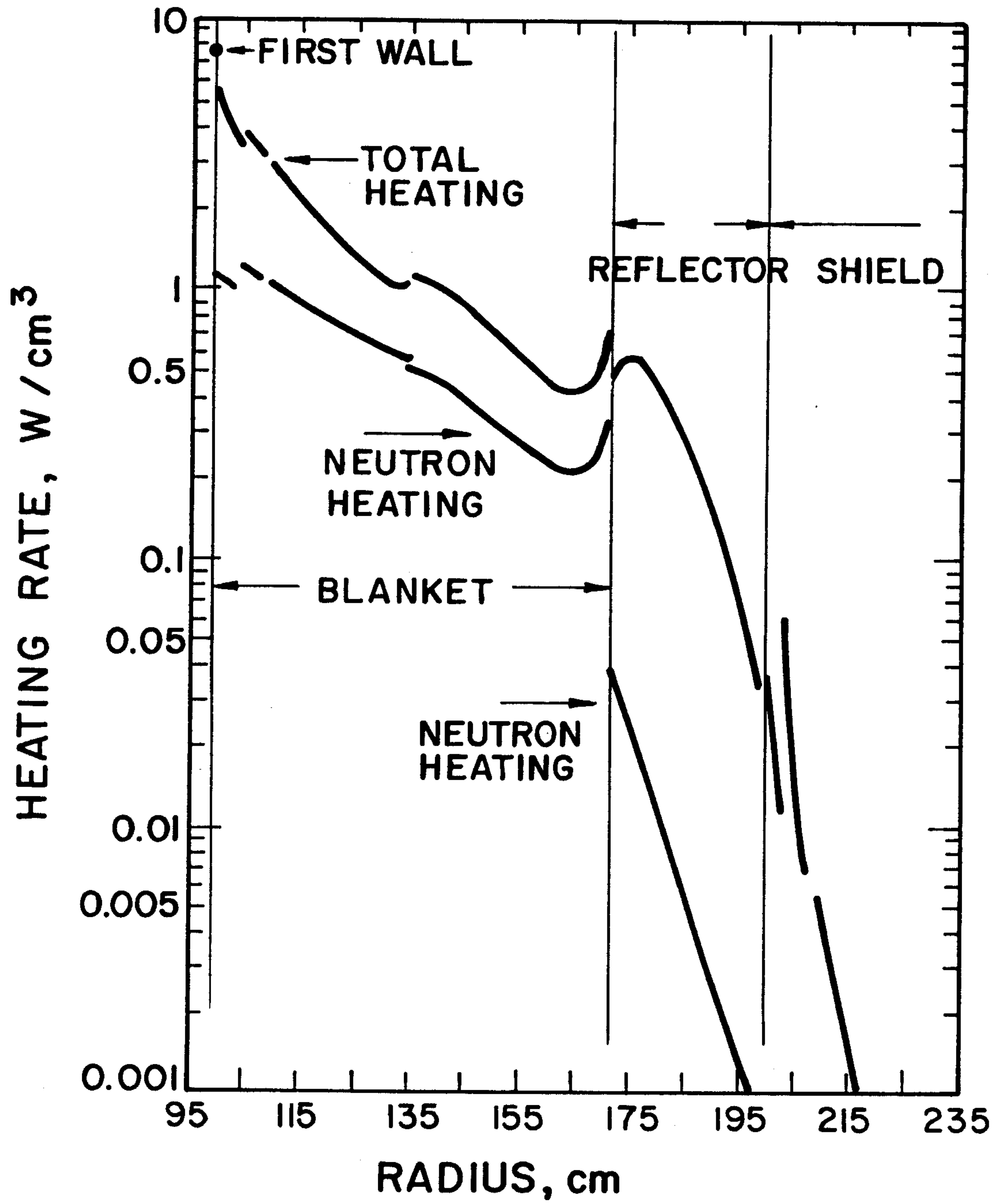
ENERGY DEPOSITED BY ZONE PER 14 MeV NEUTRON

-MeV-

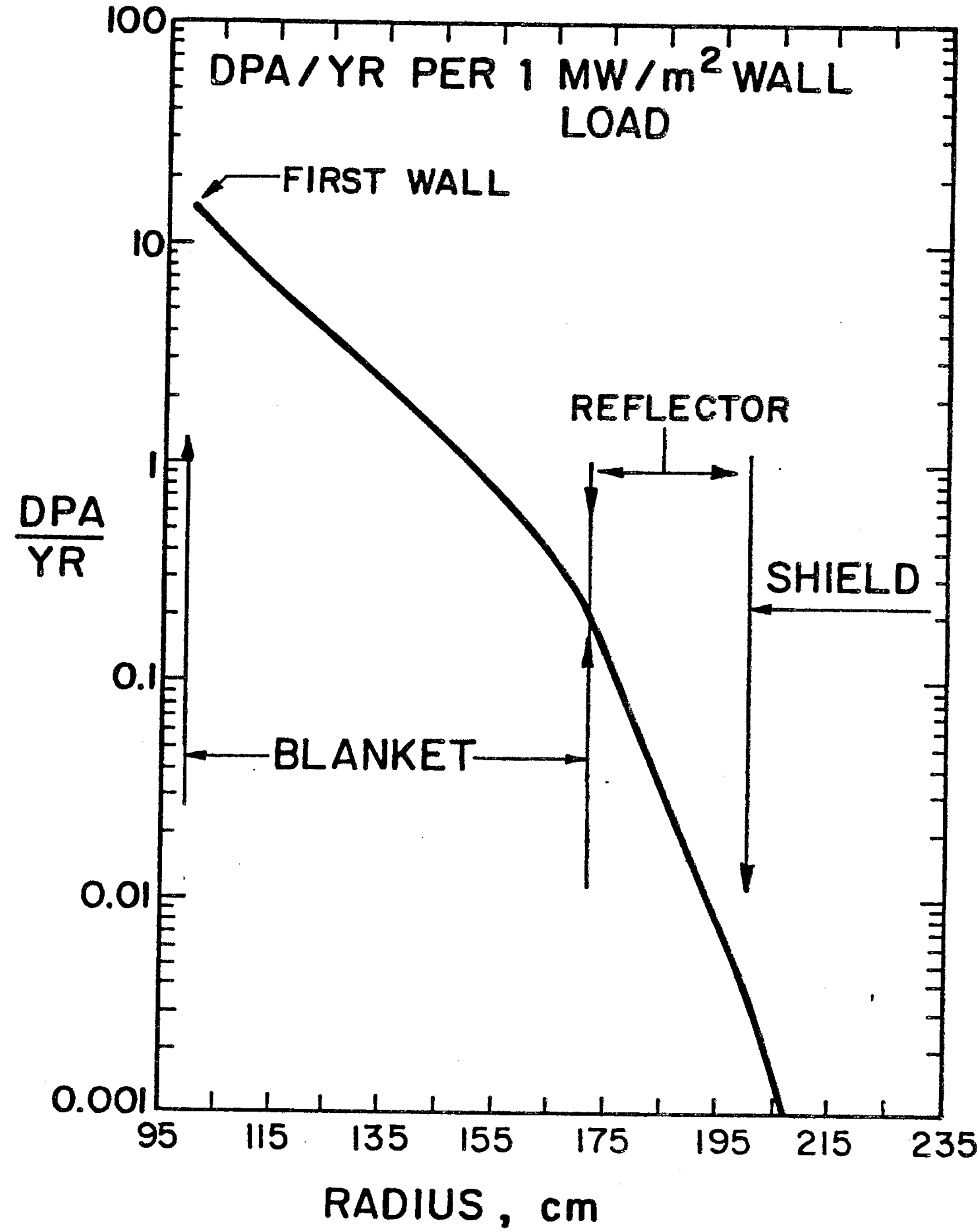
	GAMMA	NEUTRON	TOTAL
FIRST WALL	.15	.19	.34
BLANKET	10.17	6.90	17.07
REFLECTOR	1.86	.06	1.92
SHIELD	.0017	.0012	.0029

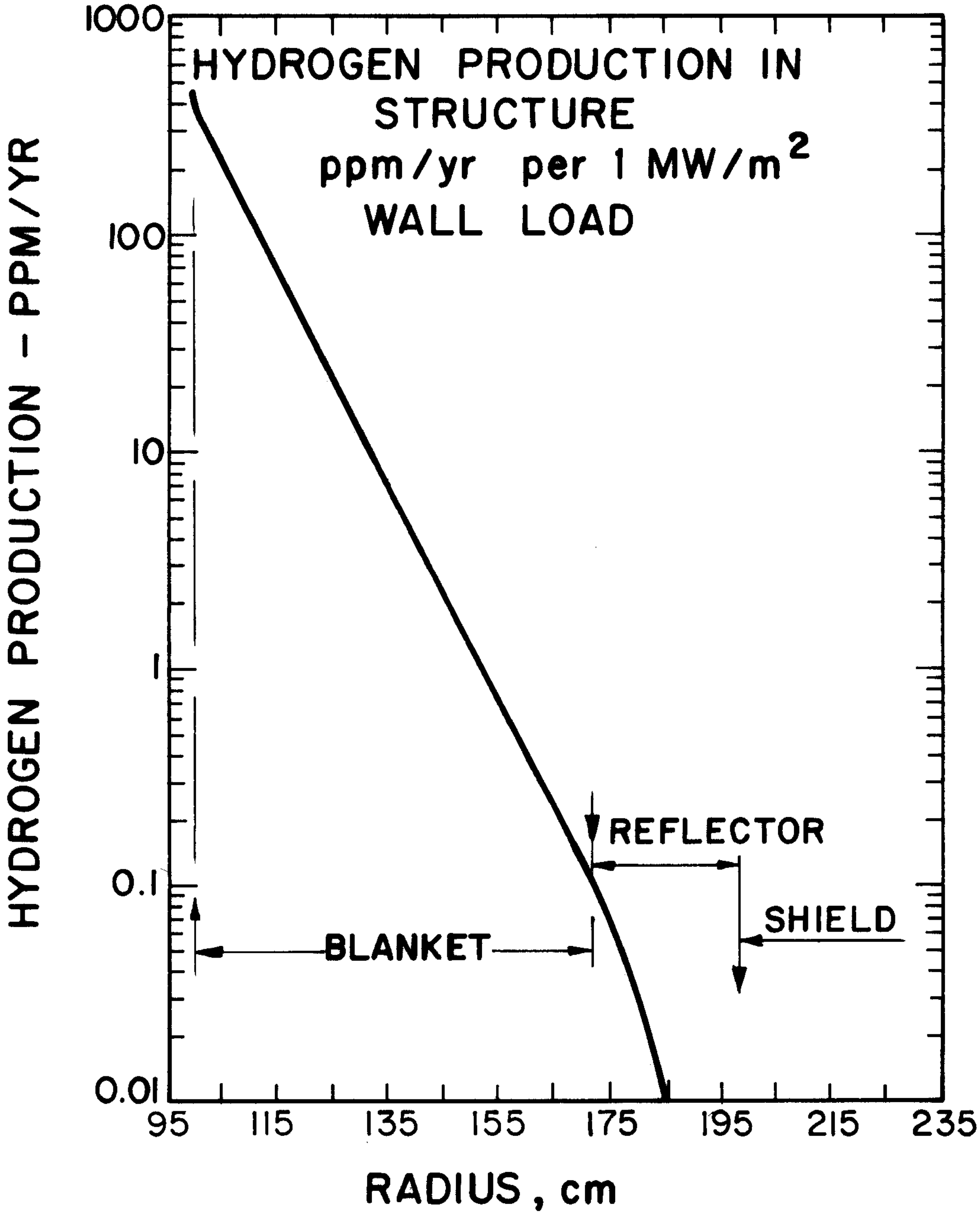
FIRST WALL RADIATION DAMAGE PARAMETERS PER YR: 1 MW/m^2 WALL LOAD

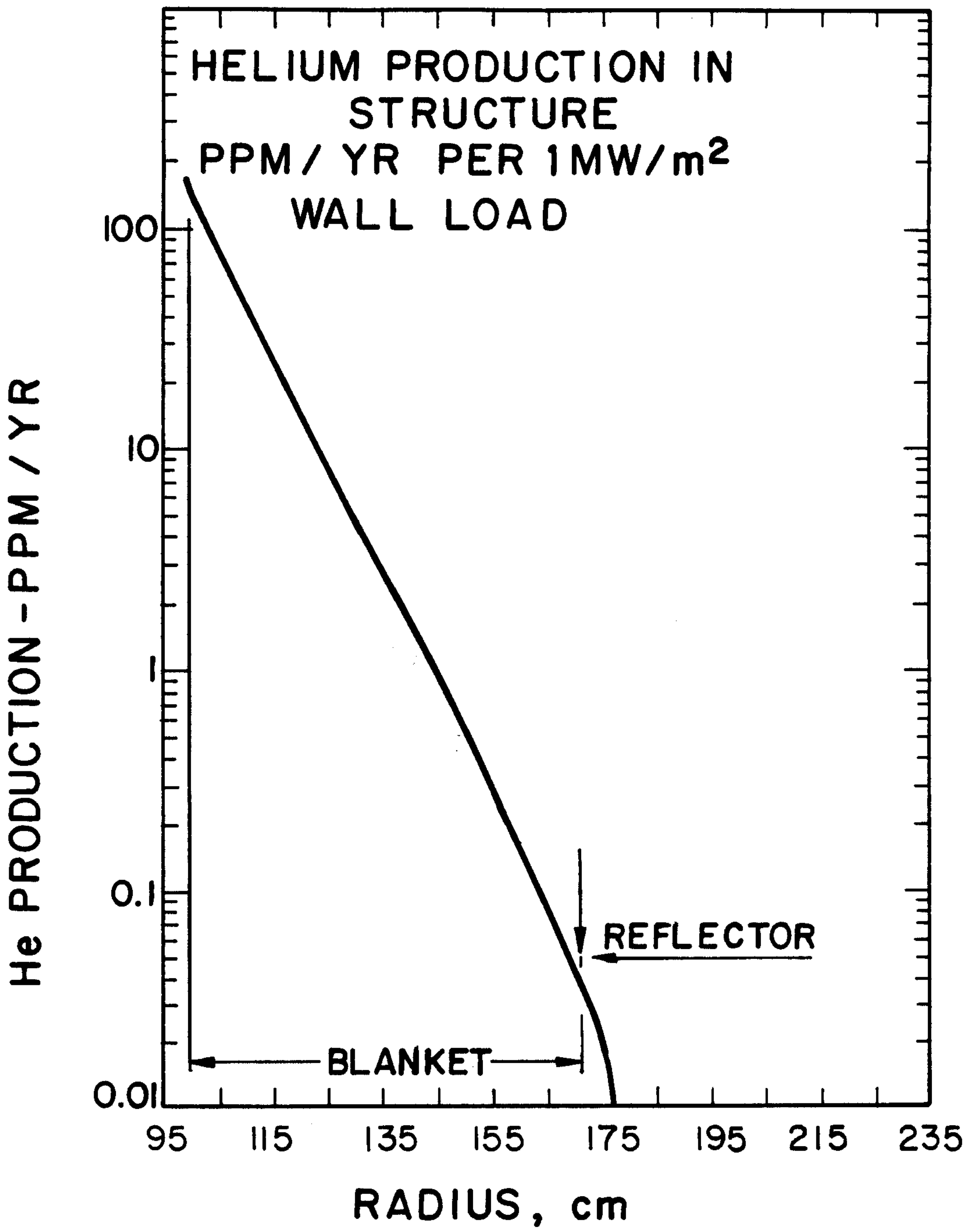
DISPLACEMENT PER ATOM	16.88
He PRODUCTION ppm	117
HYDROGEN PRODUCTION ppm	482



10
1
0.5
0.1
0.05
0.01
0.005
0.001
95
115
135
155
175
195
215
235
HEATING RATE, W/cm^3
RADIUS, cm
FIRST WALL
TOTAL HEATING
NEUTRON HEATING
BLANKET
NEUTRON HEATING
REFLECTOR
SHIELD


DPA/YR PER 1 MW/m2 WALL LOAD
FIRST WALL
REFLECTOR
SHIELD
BLANKET
DPA/YR
100
10
1
0.1
0.01
0.001
95
115
135
155
175
195
215
235
RADIUS, cm


HYDROGEN PRODUCTION IN STRUCTURE
ppm/yr per 1 MW/m2 WALL LOAD
HYDROGEN PRODUCTION - PPM/YR
RADIUS, cm
1000
100
10
1
0.1
0.01
95
115
135
155
175
195
215
235
REFLECTOR
SHIELD
BLANKET



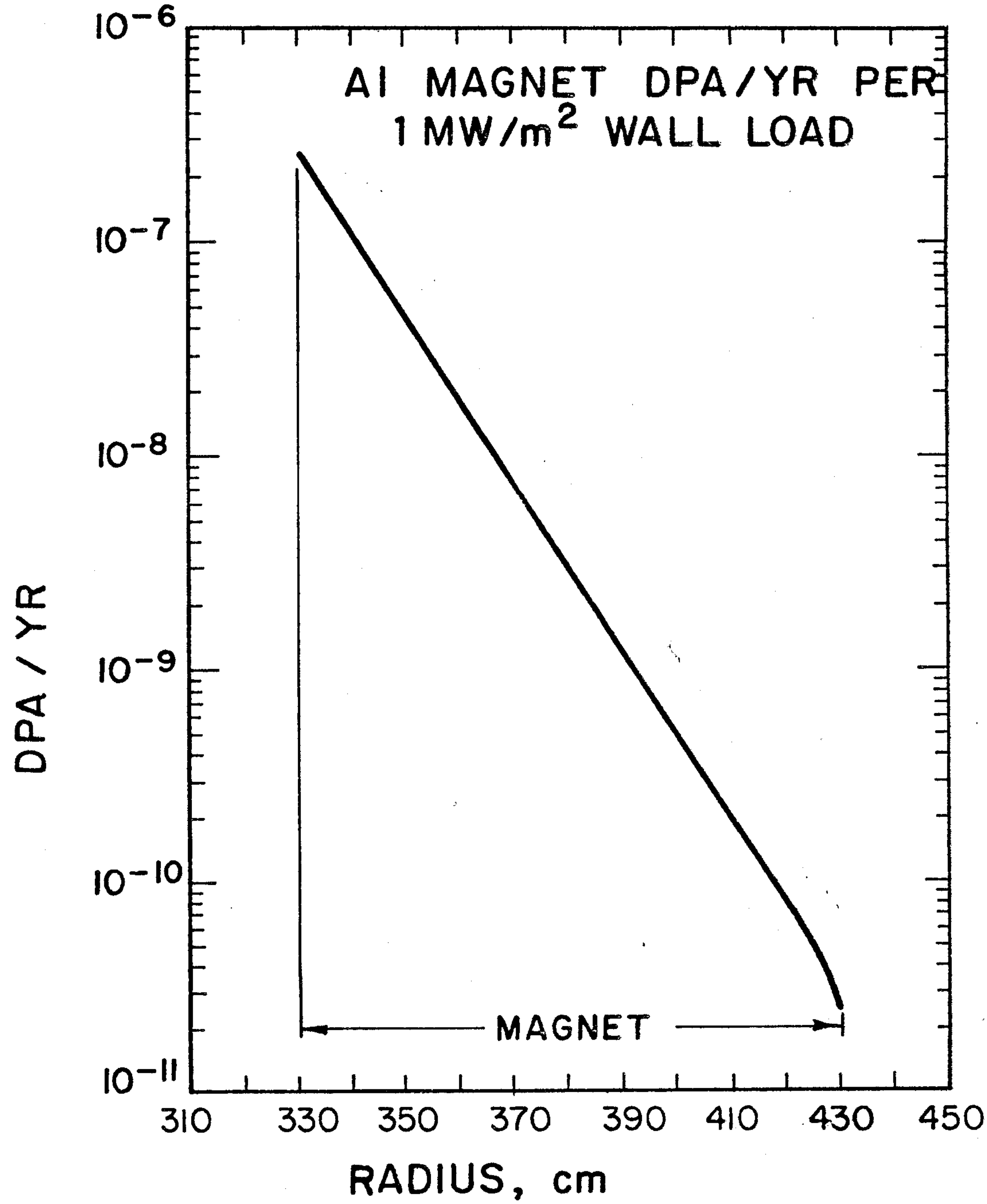
Helium production in structure.

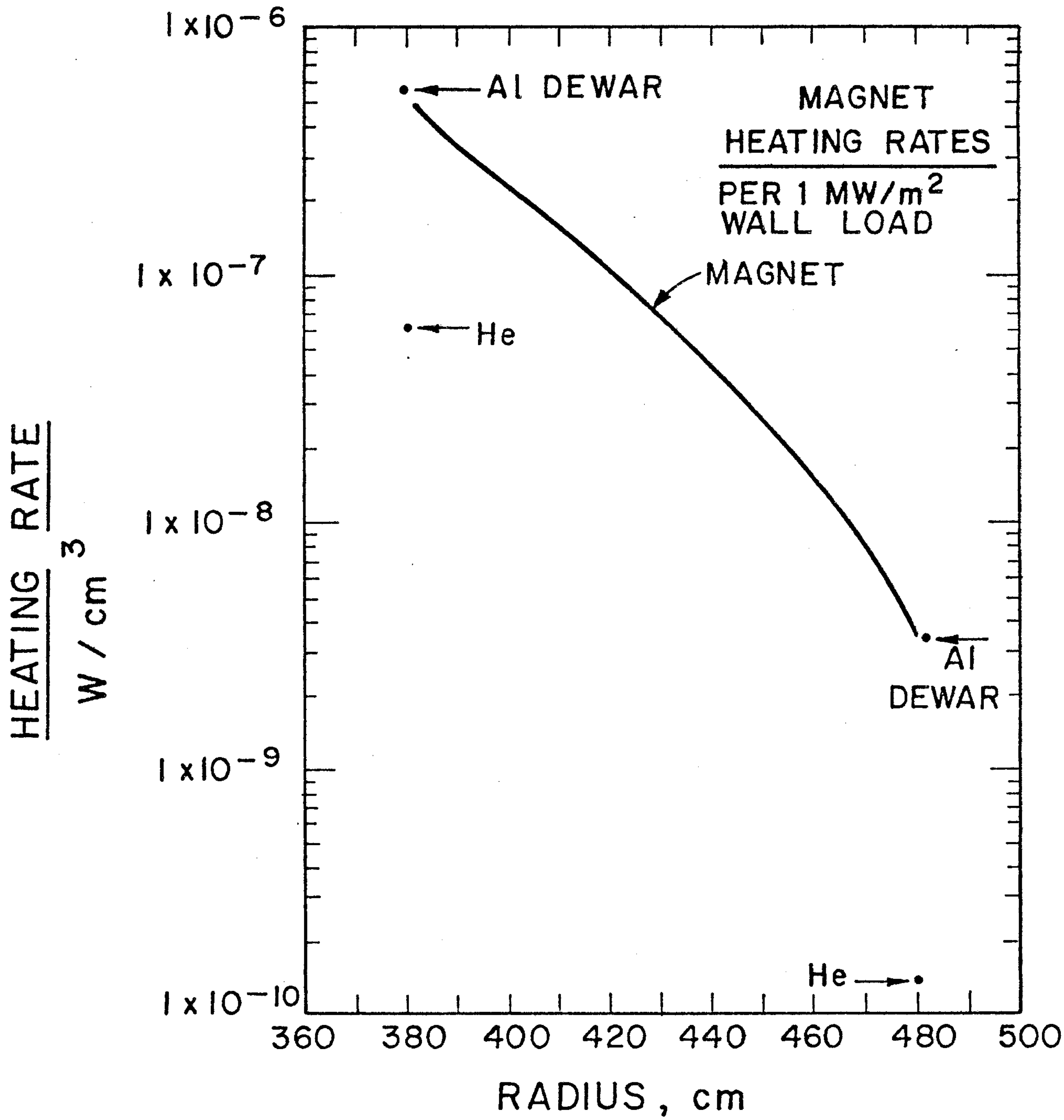
THE NEUTRON FLUENCE IN THE SUPERCONDUCTORS PRIMARILY AFFECTS THE STABILIZING MATERIAL AND RESULTS IN AN INCREASE OF THE ELECTRICAL RESISTIVITY. THE INCREASE IN RESISTIVITY IS RELATED TO THE NUMBER OF DISPLACEMENTS PER ATOM IN THE STABILIZER, WHICH IN OUR DESIGN IS ALUMINUM. THE INCREASE IN RESISTIVITY LIMITS THE MAGNET FUNCTIONS; HOWEVER, COMPLETE RECOVERY OF THE MAGNET IS POSSIBLE BY ANNEALING.

A DESIGN LIMIT OF TWO YEARS OF OPERATION WITHOUT ANNEALING WAS SET. IT IS EXPECTED THAT ANNEALING WOULD BE REQUIRED WHEN A RESISTIVITY INCREASE OF 50% OCCURRED. THIS CORRESPONDS TO 4×10^{-6} DPA.

TAKING THE MAXIMUM VALUE OF THE DPA IN ALUMINUM, WHICH OCCURS AT THE EDGE, SCALING IT TO 2.4 MW/M^2 WALL LOAD FOR A TWO YEAR PERIOD RESULTS IN A VALUE OF 1.3×10^{-6} WHICH IS WELL WITHIN THE DESIGN LIMITS. SIMILAR RESULTS WERE FOUND AT THE TOP AND BOTTOM OF THE REACTOR WHERE A DIFFERENT BLANKET MODEL WAS USED TO SIMULATE THE HEADERS.

THE RADIATION EFFECTS ON THE EPOXY AND THERMAL INSULATION USED IN THE MAGNETS ARE NOT REVERSIBLE. THUS, IT IS IMPORTANT THAT THESE LAST FOR THE LIFE OF THE REACTOR. THE LIMITS WOULD BE ABOUT 1×10^{10} RADS FOR THE THERMAL INSULATION AND $1 - 5 \times 10^{9}$ RADS FOR THE EPOXY. OUR CALCULATIONS INDICATE THAT A MAXIMUM DOSE OF 1.6×10^{6} RADS PER YEAR PER MW/M^2 WALL LOAD WILL OCCUR IN THE THERMAL INSULATION AT THE HEADERS, AND 8.6×10^{6} RADS AT THE MID-PLANE. FOR THE EPOXY A DOSE 1.5×10^{6} RADS PER MW/M^2 PER YEAR WILL OCCUR AT THE HEADERS AND 6.4×10^{5} RADS AT THE MIDPLANE. EVEN AT FULL POWER FOR THIRTY YEARS, THESE WOULD BE WITHIN LIMITS.


Al MAGNET DPA/YR PER
1 MW/m2 WALL LOAD
DPA / YR
10−6
10−7
10−8
10−9
10−10
10−11
MAGNET
310
330
350
370
390
410
430
450
RADIUS, cm


MAGNET
HEATING RATES
PER 1 MW/m²
WALL LOAD
Al DEWAR
MAGNET
He
Al
DEWAR
He
1 x 10−6
1 x 10−7
1 x 10−8
1 x 10−9
1 x 10−10
HEATING RATE
W / cm³
360
380
400
420
440
460
480
500
RADIUS, cm

Tandem Mirror Neutronics Parameters

(Based on 1 MW/m^2 Wall Load)

Blanket & Shield	
Breeding Ratio	
Li^6	1.043
Li^7	.025
Total	1.068
Energy Deposited per 14.1 MeV Neutron	
Neutron	7.166 MeV
Gamma	12.216 MeV
Total	19.38 MeV
Energy Multiplication	1.38
First Wall	
Radius	96.7 cm
Volume	182.6 cm^3/cm
Thickness	.3 cm
Power Density	
Neutron	4.41 W/cm^3
Gamma	3.52 W/cm^3
Total	7.93 W/cm^3
DPA per year/Mw/m^2	16.88
H production ppm/yr	482
He production ppm/yr	117
Energy Deposition per 14.1 MeV Neutron	
Neutron	.187 MeV
Gamma	.149 MeV
Total	.336 MeV
Breeding Blanket	
Radius	97 cm
Volume	60,700. cm^3/cm
Thickness	72.5 cm
Power Density	
Neutron	.490 W/cm^3
Gamma	.722 W/cm^3
Total	1.212 W/cm^3

Tandem Mirror Neutronics Parameters (continued)

Energy Deposition per 14.1 MeV Neutron	
Neutron	6.90 MeV
Gamma	10.17 MeV
Total	17.07 MeV
Reflector	
Radius	169.5
Volume	32,283 cm^3/cm
Thickness	28 cm
Power Density	
Neutron	.0078 W/cm^3
Gamma	.249 W/cm^3
Total	.257 W/cm^3
Energy Deposition per 14.1 MeV Neutron	
Neutron	.058 MeV
Gamma	1.86 MeV
Total	1.92 MeV
Shield	
Radius	197.5 cm
Volume	85,765 cm^3/cm
Thickness	60 cm
Power Density	
Neutron	.0012 W/cm^3
Gamma	.0017 W/cm^3
Total	.0029 W/cm^3
Energy Deposition per 14.1 MeV Neutron	
Neutron	.023 MeV
Gamma	.034 MeV
Total	.057 MeV
Percent of Total Energy	.29%
Magnets	
Thermal Insulation (Mylar)	
Radiation Dose	
Midplane	8.6×10^5 rad/yr
Header	1.6×10^6 rad/yr

Tandem Mirror Neutronics Parameters (continued)

Electrical Insulation (Epoxy)	
Radiation Dose	
Midplane	6.4×10^5 rad/yr
Header	1.5×10^6 rad/yr
DPA in Al per yr/MW/m^2	2.73×10^{-7}
Power Density	
Neutron	1.12×10^{-8} W/cm^3
Gamma	6.30×10^{-8} W/cm^3
Total	7.42×10^{-8} W/cm^3
Radius	330. cm
Volume	238,760 cm^3/cm
Thickness	100 cm

CONCLUSION

THE BLANKET AND SHIELD FOR THE TMR MEET ALL OF OUR BASIC DESIGN CRITERIA. THE BLANKET HAS A TRITIUM BREEDING RATIO OF 1.07 AND THE SHIELD ADEQUATELY PROTECTS THE MAGNETS. IN ADDITION, THE BLANKET HAS EXCEPTIONALLY HIGH ENERGY MULTIPLICATION WHICH ENHANCES THE ECONOMICS OF THE SYSTEM.